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Input Substitution in the Coal-Fired Electric Power Industry

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BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE

OF

DOCTOR OF PHILOSOPHY

IN

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Mohammad Fatoorehchie

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

ABSTRACT

Input Substitution in the Coal-Fired

Electric Power Industry

by

Mohammad Fatoorehchie, Doctor of Philosophy

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A gradual increase in the price of oil, a decline in the supply of gas, and a lag in nuclear construction leaves coal (a potential major resource for the future energy needs) as a fuel in ample supply. The major portion of the United States' electricity is generated by steam-driven generators where steam is produced by fossil fuel-fired boilers. In 1978, 47 percent of the total electricity generation was fueled by coal, up from 43 percent in 1975. Use of coal in generation of electricity has spawned numerous research projects concerning the economics of the coal-fired electric power industry.

The majority of the empirical works employed estimates of cost or production functions derived from the traditional strong separable functions (i.e., Cobb-Douglas or Constant Elasticity Substitution models). In the case of multiple-output, multiple-input models, constancy of elasticity of substitution proves to be highly restrictive. Limitations of conventional models have motivated the use of more

general models, specifically the transcendental logarithmic function which imposes no separability restriction *a priori*.

Absence of new empirical studies for the industry, provides sufficient justification for the empirical study of the economic relationship between inputs and outputs in the coal-fired electric power industry. Also absent in previous works is the element of machine mix and air pollution control factors. The analysis of substitution possibilities between inputs and the existence of a technological change form the objectives of the present study. Substitution and price demand elasticities are estimated which provide guidelines and useful information for planning and design of optimally more efficient coal-fired power plants. These estimated elasticities can be used to analyze the impacts of some selected government or industry policies, or they can provide guidance in further policy development and research.

A transcendental logarithmic multiple-input, multiple-output cost function is adapted to the cross-section data of the coal-fired electric power industry for 1973 at the plant level. The maximum-likelihood ratio test is used to empirically test the validity of various restrictions on the productive structure. The model used in this study provides for a share-specific elasticity to be computed for each price and share observation.

Results drawn from this study suggest that models with constant elasticity of substitution (i.e., Cobb-Douglas, and the Constant Elasticity Substitution and Separable models) do not appropriately

represent the structure of the United States' coal-fired electric power industry. Although the empirical findings at the industry level provide substitution elasticities smaller than one, significant substitution possibilities can be found for several vintages. Scale economies are present; and contrary to the findings for the power industry, it was found that the coal-fired power plants do not operate on the flat portion of the average cost curve.

(122 pages)

CHAPTER I

INTRODUCTION

The coal-fired electric utilities, as the major source of electricity generation, provide 38 percent of the United States electric capacity. To meet the growing demand for electricity, the industry is constantly engaged in the expansion of capacity and is expected to reach the 350,000 megawatt target by 1995, an increase of more than 68 percent (FEA, 1977b). The use of coal by electric power plants has increased steadily since 1935. It has expanded more than 300 percent since 1955, which represents a rather accelerated rate of growth of coal consumption by the industry (see Table 1).

This accelerated development of coal-fired electric power plants, prompted by recent legislation, seems to run counter to the national desire for a cleaner environment. Since a wide array of emissions are produced from the operations by coal-fired electric power plants, such as particulate matter and sulfur gases, considerable legislation has been passed to restrict particulate and stack gas emissions. Meeting these policy requirements, over the past decade has posed a difficult challenge for the electric utility industry, which is already confronted with the growing national demand for electricity. Regulated price of electricity, increasing prices of coal and labor and the existence of a time lag for rate adjustment to inflation makes the investment in utilities less attractive compared

TABLE 1

ANNUAL CONSUMPTION OF BITUMINOUS COAL AND LIGNITE BY ELECTRIC POWER UTILITIES

Year	Coal Consumption (1,000 tons)
1935	30,936
1940	49,126
1945	71,603
1950	88,262
1955	140,550
1960	173,882
1965	242,729
1970	318,921
1971	326,280
1972	348,612
1973	386,879
1974	390,068
1975	403,249
1976	447,021
1977	474,818

Source: Compiled from U. S. Congress, 1973, p. 73; FPC, 1977a, p. 70; and U. S. Department of Energy, 1978, p. 17.

with other investment opportunities and therefore causes a shortage of capital for expansion of capacity. The private sector is concerned with the rising capital requirements of pollution control devices and land reclamation regulations which cause an increase in the price of coal and therefore the price of coal-generated electricity.[1] The

[1] Table 2 provides an eight-year period of data on capital requirements for the plant and pollution control devices.

TABLE 2

COST OF AIR QUALITY CONTROL DEVICES PER KILOWATT HOUR INSTALLED CAPACITY FOR EIGHT-YEAR PERIOD 1967 THROUGH 1974 FOR FOSSIL-FUELED ELECTRIC POWER INDUSTRY

Industry Year	Plant Cost* $/kW	Cost of Air Quality Control Mills/kWh
1967	109	NA
1968	123	NA
1969	125	0.052
1970	163	0.058
1971	137	0.056
1972	150	0.060
1973	190	0.068
1974	194	NA

*Not including the charge on capital goods.

NA = Data not available.

Source: Federal Power Commission, 1977b, 1973a, 1973b, 1974, and 1975b.

public sector is concerned with the economic cost of regulatory actions imposed on the industry, and attempts are made to evaluate alternative solutions to the problems. Therefore, policies related to allocation of funds for future development require specific answers to the problems about which both the private and public sectors are concerned.

A shift to coal use in generating electricity in conjunction with the existing environmental regulations on emissions is causing changes in the relative prices of the major inputs (coal, capital, and labor) in the coal-fired electric power industry. What these changes mean for the production process is not clearly understood. Moreover, it is not clear whether the recent environmental and fuel shift policies are effective in achieving energy independence and environmental enhancement, or, whether they are conflicting goals, given the present technology of the coal-fired electric generating production process. Clearly, an understanding of that production process would be helpful in analyzing the impact that such policies impose on the industry. Information on specific issues such as the effects of changes in relative factor prices on major inputs, the introduction of certain capital components (pollution abatement equipment) as influenced by air quality standards, input substitution possibilities and technological change is an important input to the planning process of both the public and private sectors.

There are conflicting views concerning the relationships between capital, fuel and labor as factor inputs in producing electricity. Major questions often asked are as follows: (1) Can capital be substituted for fuel where fuel comprises some 78 percent of the total cost of production? (2) Are there any complementary relationships between factor inputs, particularly between capital, labor and fuel, and capital used for particulate emission control? (3) What is the degree of substitution, if any, between fuel, capital and labor inputs? (4) What are the effects of emission controls, if any, on input substitution possibilities and how do they affect efficiency?

The purpose of this study is to examine certain aspects of these questions. Particularly, the intent of the study is to provide relevant information on the input substitution possibilities that exist in the coal-fired electric generating industry, and to examine those forces which influence substitution such as a technological change and changes in relative prices. Substitution possibilities between factor inputs are measured by the elasticity of substitution, the percentage change in the input ratio induced by a given percentage change in the rate of technical substitution.

Many of the empirical studies of production relationships related to the power industry have only included labor, capital, and occasionally fuel, as their major inputs. Electricity is generally conceived as the only output. Furthermore, input substitution and technological progress have been analyzed primarily for the 1940's and 1950's. In this study, a multiple-input, multiple-output production model is used to assess input substitution possibilities and to incorporate the effects of air pollution control by including particulate emissions (collected ash) as another output. The empirical model is estimated using published data reported by the Federal Power Commission (FPC, 1976a, and FPC, 1976b).

The specific objectives of this dissertation are to empirically estimate the substitution possibilities between inputs and provide a test of the existence of technical change within the industry. Data on inputs and outputs for the coal-fired electric power industry on a plant-by-plant basis are used, to estimate substitution and transcendental logarithmic (hereinafter referred to as the translog) cost function is used to obtain measures of existing substitution possibilities and technological change. The translog form is a more flexible function and imposes no restrictive assumptions (such as a homothetic production structure) or *a priori* restrictions on substitution possibilities.

Background on Air Pollution Control

The coal-fired electric power industry has, for some time, been under constant pressure for compliance with air pollution standards. The only relaxation of the standards that have appeared in recent years are: (1) New Source Performance Standards (NSPS) of 1974 which determine the emission limitations and require the use of Best Available Control Technique (BACT) for an emission source (FEA, 1977a); and (2) the Clean Air Act Amendment of 1977 which relaxed NSPS standards and the required regional adoption of the State Implementation Plans (SIP) provisions (U.S. Senate, 1977). Since inputs used in particulate emission (the major pollutant) control play an important role, a brief chronological review of the air pollution control problem and regulations is given below.

In 1955, the Air Pollution Control Act was passed by Congress in an effort to help states and localities in pollution control and related research programs. The Clean Air Act passed in 1963, which amended the 1955 Act, authorized direct grants to states and localities to develop pollution control programs. The 1963 Clean Air Act was amended in 1965, and was primarily directed to the regulation of motor vehicles. Another amendment came in 1966 which expanded the federal aid program in air pollution control. A 1967 amendment directed the Department of Health, Education and Welfare to design broad atmospheric areas for the United States and also established the Presidential Air Quality Advisory Board to strengthen the previous provisions of the earlier legislation. Then came the Clean Air Act Amendment of 1970, which authorized the Environmental Protection Agency to adopt the ambient air quality standards (Perkins, 1974). Standards were adopted in two categories: (1) Primary standards to protect the public health "allowing an adequate margin of safety," and (2) secondary standards to protect the public welfare "from any known or anticipated adverse effects" (Megonnell, 1975). Since 1970, numerous amendments have been added to the Clean Air Act Amendment of 1970. One of these amendments came through The Energy Supply and Environmental Coordination Act of 1974 (EPA, 1976). Under the provisions of the Act, the Federal Energy Administration has been granted the power to prohibit the use of petroleum products and natural gas at electric power plants in order to conserve fuel.

The uncertainties of the supply of oil and natural gas and the growing dependence in the United States on coal for generation of electricity led to the Clean Air Act Amendment of 1977. The 1977 amendment provided the necessary grounds for a revision of the criterion for sulfur oxides in parallel with revisions restricting particulate matters. Table 3 provides a summary of current national ambient air quality standards for particulate and sulfur dioxide emission.

TABLE 3

SUMMARY OF CURRENT NATIONAL AMBIENT AIR QUALITY STANDARDS OF PARTICULATE AND SULFUR DIOXIDE EMISSIONS UNDER NSPS

Description of Law	Primary Standards	
	SO_x Emission Standards	
Clean Air Act Amendment of 1977	Daily arithmetic mean of 85 percent sulfur dioxide reduction.*	An emission floor in the range of 0.5 to 0.8 pound of sulfur dioxide per million BTUs.**
	Particulates Standards	
	0.3 pounds per million BTU emissions ceiling for total suspended particulates.*	Standards are to be set at a level which would not preclude the use of electrostatic precipitators, which is an emission level in the range of 0.05 to 0.08 pounds of particulates per million BTUs.**

*Proposed by Environmental Protection Agency.

**Suggested by the Department of Energy.

Source: Bureau of National Affairs (1978).

In the last decade, numerous advances to control pollutants in coal-fired electric power plants have been developed. Various new possibilities have surfaced, and several large pilot electric power plants using these advances in technology are presently on line.

Technology in the field of particulate matter emission control has adequately advanced at commercial levels. Electrostatic precipitators with an efficiency rating of 95 to 99.9 percent are widely used by the industry. The capital cost of particulate matter control devices run between \$60 and \$90 per kilowatt.

Coal-fired electric power plants are responsible for 60 percent of the sulfur dioxide emitted into the atmosphere. Because of inadequacy of technological progress, and to a degree, because of infeasibility in adopting the available devices, the industry was lagging in compliance with sulfur dioxide standards until the summer of 1973. A national public hearing in the fall of 1973 launched a new development to move the industry toward compliance with sulfur dioxide's primary standards. After testimony hearing, the panel concluded that the basic technological problem with flue gas desulfurization had been solved, and it could be applied at a reasonable cost. The capital cost of flue gas desulfurization systems on existing plants ranges from \$39 to \$108 per kilowatt with most estimates falling in the range of \$50 to \$65 per kw (Journal of Air Pollution Control Association, 1974).

Currently, compliance with new source and primary standards for particulate matter is accepted within the industry. However, compliance with sulfur dioxide emission primary standards remains a major control problem and there have been major debates between the industry and regulatory agencies, particularly at the time of permit application.

CHAPTER II

REVIEW OF LITERATURE

Several attempts have been made to study the production process of the electric power generating industry in the United States and England. Single-output, multiple-input models representing a production function or a cost function have been the primary empirical relationships used. This survey of literature is a summary of different approaches taken by earlier investigators in measuring cost and production relationships in the steam-electric power industry.

Many of the empirical studies of production relationships have included labor, capital and occasionally fuel as their major inputs, and electricity as the only output. In these studies, the plant was used as the unit of observation and was assumed to have machines of the same size and/or vintage.[2]

Lomax (1952), analyzed the relationship between output and costs using 1947-1948 data for steam electric plants in two regions of the United Kingdom, each plant operating at least 6600 hours. Using cross-section data for each region, he estimated two exponential functions relating the output to cost. In this study, the variance in vintage and machine-mix of the plant was not considered; hence, interpretation of the effects of the movement along the production

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[2] Adoption of such assumption, requires that total output and total fuel input to be the same for each machine.

function were limited. His findings indicated that the cost per unit of generating capacity declined as the size of the plant and the load factor increased.

In order to estimate the long-run cost function, Johnston (1960), carried out two cross-section studies on 73 British steam-electric firms for the years 1946-1947 and 1938-1939. The operation of plants, when observed in the cross-sections, was assumed to take place at the point of minimum average cost on the short-run average cost curves of particular plants. Since no consideration was made for differing machine technology for plants within the firm, the estimated regressions cannot be said to be long-run cost functions.[3] Johnston concluded that a linear relationship between total variable costs and output for firms of varying size exists within the industry.

Using a sample of 235 plants, Komiya (1962), studied the production process of United States electric power plants built in the period 1930 to 1956. In order to capture technological change and the related shifts in the production function, a logarithmic single-output, multiple-input Leontief model was estimated with no optimization behavior assumed. The size of a given plant was defined through the average size of the generating units within a plant. Technology was treated at the factor level and no allowance given to the problem of machine mix. Using covariance analysis, Komiya found

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[3] A cross-section analysis with no allowance made for technological change can produce a long-run total variable cost curve only if the technological change implies the introduction of a plant with larger capacity. (For further discussion, see Galatin, 1968.)

that average size and the number of generating units had a significant effect on the equipment cost per generating unit. He concluded that the effect of technological change has been to reduce the fuel requirements in electricity production.

To measure the degree of returns to scale in the production of electricity, Nerlove (1963), studied 1955 cross-section data on 145 United States' electric utility firms. The production process was characterized by a Cobb-Douglas production function with parameters estimated through an implied cost function under a cost minimization behavior.

The notion of a production function is most appropriately applied to individual plants, since the plant is the most basic unit of production. Nerlove conducted his analysis at the firm level which precludes any consideration of machine-mix in terms of the size of the units in a plant, and that of plant-mix in terms of the number and sizes of plants in a firm. Each firm was assumed to be at a particular point of its long-run expansion path and long-run cost curve. He found that supply of electricity was characterized by increasing returns to scale where the degree of such return was a decreasing function of the output level.

Barzel (1964), estimated the input functions for labor and fuel in the steam-electric power industry using U.S. data for the period 1941-1959. His sample included data from 220 plants, with one plant being the unit of observation. The degree of returns to scale for labor was found to be greater than that for fuel. To capture the effect of technological change, Barzel estimated a separate equation for plants of each vintage. He found that the effect of technological change is a relatively small 9.6 percent reduction in fuel requirements per kilowatt hour for the period.

Dhrymes and Kurz (1964), investigated the possibility of technological change and the existence of returns to scale in the United States steam electric power industry. Using a sample of 362 plants constructed during 1937 to 1959, they examined the productive process by employing a generalized constant-elasticity-of-substitution production function. That unit of observation was a plant observed at "normal" operation levels during one-year periods. They stratified their sample by vintage and size; and assumed the cost minimization hypothesis of Nerlove (1963). Their results indicated that a uniform increasing returns to scale to labor prevailed in the industry. Barzel, Dhrymes and Kurz, did not account for the biases which exist in their estimates as a result of machine-mix variability between plants.

Christensen and Greene (1976) estimated economies of scale for the U.S. electricity producing industry. To model the structure of production in the industry, they used the cost function approach. Using cross-section data for 114 firms for 1955 and 1970, they estimated the range over which economies of scale persist. Their findings suggest that significant scale economies did exist in 1955, but that by 1970 the majority of electric power generation firms had exhausted scale economies. Using a single-output translog cost function approach, they estimated the economies of scale for the industry, ignoring the problem of machine and fuel mix in the process. The fuel mix problem introduces a bias in the results because each fuel mix requires different technology.

Biases resulting from the neglect of fuel mix and machine mix considerations have not been corrected in any new empirical studies of the industry. In addition, little has been done to include air pollution control equipment and emissions. These errors and oversights justify a new empirical study of the coal-fired electric power production process in a multiple-input, multiple-output context.

CHAPTER III

ECONOMIC MODEL

The traditional homogeneous and additive models of studies related to production and cost functions played an important role in the formulation of statistical tests of the theory of production. These models, such as the Cobb-Douglas or constant elasticity of substitution (CES) functions, have made significant contributions in the analysis of one-output, two-input functions which are traditionally used in economics. However, these constant elasticity of substitution formulations are highly restrictive[4] when used in the multiple-input, multiple-output context. In the CES function the partial elasticity of substitution between any pair of inputs is equal, except for the Uzawa's (1962) nested CES function, which rules out the complementary relationship between inputs *a priori* (Burgess, 1975). Strong separability and self-duality are also implicit properties of CES and Cobb-Douglas functions. These properties impose further limitations in the estimation process which should be justified empirically rather than being imposed *a priori*. Limitations of conventional models have motivated the

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[4]". . . a commodity-wise additive (strong separability) and homogeneous production possibility frontier is unsuitable for representation of production possibilities with several outputs and several inputs." (Christensen, Jorgensen, and Lau, 1973, p. 30).

use of more general models, specifically the translog function which was initially proposed by Christensen, Jorgensen and Lau (1971). The model is flexible enough to accommodate relevant hypotheses for the evaluation of different input substitution possibilities in a multiproduct multifactor characterization. In this study, the neoclassical cost function approach is applied to model the structure of production in the coal-fired electric power industry. More specifically, a multiple-input, multiple-output translog cost function facilitates the estimation and analysis of the partial elasticity of substitution for pairs of inputs (Burgess, 1975). The model is not constrained by assumptions of homotheticity or constant substitution elasticities.

In empirical investigations, a production function or a cost function is often used to suggest an underlying production structure. The choice of which of the two functions to use depends upon the type of data suitable for particular studies. Estimation of a production function proves to be more desirable when the output level is indogenous, and the estimation of the cost function is more attractive when the output level is exogenous (Christensen and Greene, 1975).

Since the electric power industry in the U.S. is a regulated business firm, its economic and technical environment is quite different from other business entities. Electric utilities are required to supply all the electric power which is demanded at regulated prices, while competing with all other industries for inputs. Therefore, since output and factor prices are assumed exogeneous and input levels become endogeneous to the firm's decision, the cost function approach has been chosen for the study.

Methodology

The procedure followed in this study is the adaption of a translog cost function to cross-section data. This functional form, first proposed by Christensen, Jorgensen, and Lau (1973), is a second-order local approximation to an arbitrary underlying function about a point by a logarithmic Taylor series expansion. The function is flexible with no *a priori* restriction on substitution possibilities among the factors of production.[5] The cost function can be expressed as:

$$C(Y_K, P_i) = \min \{P_X' | F(X) \geq Y\}$$

where $P = (P_1, P_2, \ldots, P_n)$ is the vector of factor prices; $Y = (Y_1, Y_2, \ldots, Y_K)$ is the vector of joint outputs;[6] X is the vector inputs; and F is the given production function (Diewert, 1974). $C(Y_K, P_i)$ is defined for all $P \geq 0$, $Y > 0$, and $X \geq 0$; therefore, local monotonicity and concavity conditions are maintained (Diewert,

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[5] See Christensen, Jorgensen, and Lau (1971); Christensen and Greene (1976); and Humphrey and Moroney (1975).

[6] This rules out the possibility of an interaction between production processes except through the primary inputs (Hall, 1973). This form allows a statistical test of nonjointness of the outputs.

1974). The behavioral assumption underlying the model (subject to test) is expressed by:

$$\min PX$$
$$\text{s.t. } (y;X) \in Y$$

where X is the vector of inputs, P is the vector of factor prices, y is the vector of outputs and Y is the production set. This functional form allows for specification of a nonhomothetic function with a nonconstant share of inputs; it also provides for a varying return to scale specification with the following translog form:

$$\begin{aligned} \ln c = \lambda_o &+ \sum_{k=1}^{n} \gamma_K \ln Y_K + 1/2 \sum_{k=1}^{n} \psi_K (\ln Y_K)^2 + \sum_{i=1}^{n} \alpha_i \ln P_i \\ &+ 1/2 \sum_{i=1}^{n} \beta_{ii} (\ln P_i)^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln P_i \ln P_j \\ &+ \sum_{i=1}^{n} \sum_{k=1}^{n} \delta_K \ln P_i \ln Y_K + \sum_{k=1}^{n} \sum_{k'=1} \omega_{KK'} \ln Y_K \ln Y_{K'} \end{aligned} \tag{1}$$

for

$$K,\ 1, \ldots, n\ ;\ \text{and } K \neq K'$$
$$i, j = 1, \ldots, n$$

where C and Y are total costs and outputs, and P_i is the price of the ith input.

The continuous increase in total cost as a function of factor prices is determined by n equations:

$$\frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_{j=1}^{n} \beta_{ij} \ln P_j + \sum_{k=1}^{n} \delta_K \ln Y_k$$

$$i,j = 1,\ldots, n$$

$$k = 1,\ldots, n \tag{2}$$

Shephard's lemma states that, "along the minimum cost expansion path, the equilibrium employment of the ith input . . . represents the marginal cost" (Shephard, 1970, p. 171):

$$\frac{\partial C}{\partial P_i} = X_i \tag{3}$$

When the production possibility plane is tangent to the iso cost surface, and production is defined at the point of tangency between the transformation hyperplane and the cost cone. That is to say, each observed factor input is equal to the factor demand derived from the cost function, and each price is equal to the marginal cost derived from the cost function. For the cost function, defined by $C(Y_k, P_i)$ or the set $L(Y_k)$, the following relationship holds (Shephard, 1970);

$$\frac{\partial c}{\partial P_i} = X_i \tag{4}$$

For the transformation function, defined by $t(y_k, X_i)$ or the set $L(Y_k^*)$ which represents the available technology the following equality pertains (Jacobsen, 1970; Hall, 1973):

$$\frac{\partial F}{\partial Y_j} = X_i \quad \text{where } Y_j = F(X_1, X_2 \; . \; . \; . \; . \; x_n) \tag{5}$$

The two sets $L(Y_K^*)$ and $L(Y)_K$ can be thought of as polar closed convex sets (Rockafellar, 1970)

$$\frac{\partial C}{\partial P_i} = \frac{\partial F}{\partial Y_j} = X_i \tag{6}$$

If Shephard's lemma holds, then the ratio of marginal costs of two goods Y_i and Y_j will be equal to the marginal rate of transformation between them:

$$\frac{\partial C/\partial Y_i}{\partial C/\partial Y_j} = \frac{\partial T/\partial Y_i}{\partial T/\partial Y_j} \tag{7}$$

where T represents the transformation function:

$$T = t(Y_k, X_i) \tag{8}$$

By definition, the relative shares in total cost are:

$$N_i = \frac{P_i X_i}{C} \tag{9}$$

where N_i is the relative share, and X_i is the level of the ith input.[7]

Substituting (3) into (9),

$$N_i = \frac{\partial C}{\partial P_i} \cdot \frac{P_i}{C} = \frac{\partial \ln C}{\partial \ln P_i} \tag{10}$$

yields the relative shares on the cost minimization expansion locus, which are functions of output levels and factor prices. From (2):

---

[7]Note, with the assumption of the cost minimization behavior, (3) yields the factor demand functions.

$$N_i = \frac{\partial \ln C}{\partial \ln P_i} = \alpha_i + \sum_{j=1}^{n} \beta_{ij} \ln P_j + \sum_{k=1}^{n} \delta_k \ln Y_K \tag{11}$$

This system of share equations establishes the basis for empirical estimation of parameters of the cost function and the relevant elasticities. The testable hypotheses for input substitution are derived from this multiple-output, multiple-input framework. The partial substitution elasticities as defined by Allen (1938) are calculated from the estimates of the β_{ij}'s. The point estimates of Allen's partial elasticities of substitution (σ_{ij}), which will be used to evaluate the separability restrictions, are:[8]

$$\sigma_{ij} = \frac{\beta_{ij}}{N_i N_j} + 1 \qquad \text{for all } i \neq j \tag{12}$$

$$\sigma_{ii} = \frac{\beta_{ii} + N_i(N_i - 1)}{(N_i)^2} \qquad \text{for all } i \tag{13}$$

The substitution elasticities are not output specific because the factor share (N_i) explicitly accounts for all outputs:

$$N_i = f(P_i, Y_k) \qquad i, k = 1, \ldots n$$

where P_i is the vector of factor prices and Y_k the vector of outputs. Price elasticities of factor demand (η_{ij}) are obtained from the following relationships:[9]

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[8]Such inferences can be used to evaluate the effect of restrictions on the industry by determining substitution and complementary relationships.

[9]See Binswanger, 1974.

$$\eta_{ij} = \sigma_{ij} \cdot N_i \qquad \text{for all } i \neq j \tag{14}$$

$$\eta_{ii} = \sigma_{ii} \cdot N_i \qquad \text{for all } i \tag{15}$$

Demand and substitution elasticities are functions of β_{ij}'s (i and j = 1,..., n) and the cost shares N_i's (for i, j = 1,...,n), which are independent of the coefficients of the underlying production function (i.e., λ_o, γ_K, Ψ_K, and $\omega_{KK'}$).[10]

Separability Test

The nature of the elasticity of substitution can be empirically tested through the functional separability test procedure. Separability can be imposed on the translog form by appropriate parametric restrictions.

Consider the set of inputs, F, K, and L in the production process: If an ordered triple is taken (i.e., F, K, and L), then the following requirement determines the necessary conditions for Allen's partial elasticity of substitution (AES) to be variable, constant, or zero. Separability of inputs implies the following condition: F and K are functionally separable from L if the marginal rate of technical substitution between F and K, equivalent to the ratio of marginal costs is independent of the level of L, that is:

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[10]Since the price of outputs are not available, revenue function may not be derived; therefore, direct inferences to the elasticity of transformation is not possible.

$$MRT_{K,F} = \frac{F_F}{F_K} = \frac{MC_F}{MC_K} \tag{16}$$

where F_F and F_K are the marginal products, and MC_F and MC_K are the marginal costs of F and K, respectively.

If the price of L is increased, given the prices for F and K, the marginal cost schedules related to K and F may shift proportionally. Assuming an augmented increase in price of L (Hicks, 1970), then the AES between F and L will be the same as that between K and L (Berndt and Christensen, 1973a). That is, $\sigma_{FL} = \sigma_{FK}$ which implies (for proof see Russell, 1975):

$$\beta_{FL} N_K - \beta_{LK} N_F = 0 \tag{17}$$

This restriction can be treated as a testable hypothesis. Rejection of the hypothesis implies that the σ_{ij}'s are variable. If the hypothesis cannot be rejected (σ_{ij}'s are constant), then a test can be made to determine whether a specific σ_{ij} is equal to zero (fixed proportion relationship), as a necessary condition for a fixed proportion relationship, equation (17) must be satisfied.

Using the three-input case (F, L, and K) and differentiating the cost function with respect to the price of K, separability requires that:[11]

$$\frac{\partial \left(\frac{MC_F}{MC_L}\right)}{\partial P_K} = MC_F \left(\frac{\partial MC_F}{\partial P_K}\right) - MC_L \left(\frac{\partial MC_L}{\partial P_K}\right) = 0, \tag{18}$$

[11]See Berndt and Christensen, (1973a) and Russell (1975).

Define N_F and N_L as the shares of the inputs as:

$$N_F = \frac{\partial \ln C}{\partial \ln P_F} > 0 \qquad \text{and } N_L = \frac{\partial \ln C}{\partial \ln P_L} > 0 \tag{19}$$

which implies that the shares are positive in the feasible range. This is equivalent to:

$$N_F = \frac{\partial C}{\partial P_F} \cdot \frac{P_F}{C} = MC_F \cdot \frac{P_F}{C} \tag{20}$$

$$N_L = \frac{\partial C}{\partial P_L} \cdot \frac{P_L}{C} = MC_L \cdot \frac{P_L}{C} \tag{21}$$

Division of (20) by (21) yields the ratio of marginal costs used in derivation of conditions for separability:

$$\frac{MC_F}{MC_L} = \frac{N_F}{N_L} \cdot \frac{P_L}{P_F} \tag{22}$$

The shares are:

$$N_F = \alpha_F + \Sigma\beta_{FK}\ln P_K + \Sigma\delta_{FK}\ln Y_K \tag{23}$$

$$N_L = \alpha_L + \Sigma\beta_{LK}\ln P_K + \Sigma\delta_{LK}\ln Y_K \tag{24}$$

Separability of F and the L input from K is expressed as:

$$\frac{\partial \left(\frac{MC_F}{MC_L}\right)}{\partial P_K} \equiv 0 \qquad \text{for } F \neq L \neq K \tag{25}$$

That is,

$$MC_F \cdot MC_{FK} - MC_L \cdot MC_{LK} = 0, \tag{26}$$

Equation (26) can be written as (Blackorby, Primont, and Russell, 1974; and Humphrey and Moroney, 1975):

$$N_F \frac{\partial(N_L)}{\partial P_K} \equiv N_L \frac{\partial(N_F)}{\partial P_K} \tag{27}$$

which is equivalent to (Berndt and Christensen, 1973b):

$$B_{LK} N_F = B_{FK} N_L \tag{28}$$

Substituting for N_L and N_F:

$$\alpha_L \beta_{LK} - \alpha_F \beta_{LK} + 2 \ln Y_K (\delta_{FK}\beta_{LK} - \delta_{LK}\beta_{FK}) = 0 \tag{29}$$

Therefore, the condition for Equation (29) to be satisfied requires that:

$$\beta_{FK} = \beta_{LK} = 0$$

Linear separability of F and L from K, and the existence of a unitary elasticity of substitution, can be verified empirically by testing if $\sigma_{ij} = 1$ (or $\beta_{ij} = 0$).

Data

The data are taken from: (1) The Federal Power Commissions' (FPC) Annual Reports (Steam-Electric Plant Cost and Annual Production Expenses--1973 (FPC, 1976b), (2) Steam Electric Plant Air and Water Quality Control Data--1973 (FPC, 1976a) (hereinafter referred to as FPC reports and FPC air and water quality reports), and (3) the Moody's Municipal and Governmental Manual (Hanson, 1974). The unit of observation being one plant. The sample of 80 plants covers 80 percent of the total generation of electricity by coal-fired electric power industries during 1973.

The machine mix of a plant is an important factor to be considered in production studies. The optimum utilization of machines in the plant requires the allocation of output to machines which minimize total variable cost. The electrical load fluctuates during the day, so at certain times the plant operates at less than total capacity. Thus, if the optimization procedure is followed, some machines may not be operated at all, and some machines may be operated at less than full capacity during slack hours. In previous empirical studies, the samples contained plants that had a machine-mix of different sizes and/or vintages, but all units were assumed to be the same size and utilized at the same rate, introducing bias in technological change and returns to scale studies. To minimize the problem of machine mix, where different types and sizes of turbogenerators and boilers are being installed in one plant, only data from plants with one generating unit or units of the same vintage have been used.

Vintage

Most of the empirical studies related to the electric power industry have paid little attention to technological change through time. Komiya (1962), Christensen and Greene (1976) are exceptions to this general criticism to some degree. Units of production of electricity can be assumed to belong to the same production surface only if all new units have been introduced to the system with no delay. In industries where fixed capital (mainly equipment) plays an important role, technological change must be accurately distinguished over time.

In the present study, the sample[12] is stratified into three time strata representing a period in which the production units were installed and on-line operation[13] was started. Each class is called a vintage as follows:[14]

Vintage	Period
Vintage One	1941 to 1953
Vintage Two	1954 to 1961
Vintage Three	1963 to 1973

Quality of data

A generating unit may be connected to load, or be "hot" but not connected to load.[15] Hence, the nameplate capacity in megawatts, as reported by the FPC, does not provide an ideal measure of the level of output.

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[12]Only those coal-burning plants that produce steam for generation of electricity that are reported in FPC reports, are used in this study (data are presented in Appendix C).

[13]These vintages are subject to statistical tests as presented by the empirical results in this study.

[14]See Appendix C, Column (YR) for the year of on-line operation for each plant.

[15]Implying the boilers are fully operational but the generators are not connected to load.

To measure the degree of utilization of units, the number of hours generating units were "hot" but not connected to load and the number of hours that they were connected to load are required. Because of a lack of data on these measures, all plants in this study are assumed to have the same average level of efficiency in utilizing machinery within each vintage.[16]

Because of the inadequacy of data, the total generated electricity in million kilowatt hours is used as a measure of output. Data on total number of hours of total laborers involved in the generation of electricity were not available. Therefore, unadjusted figures on "annual average number of employees" are used as a measure of labor input. The "annual average number of employees," is not an ideal measure of the labor input. The "average number of employees" per plant covers operation, supervision, and engineering; but, depending upon the individual firm, it may or may not include the maintenance or repair labor. This measure also excludes differences between firms that have different working days, weeks, or conditions that result in the variation of the labor input over time.

Empirical results for labor and machinery utilization must be viewed with some caution. The degree of utilization and the number of hours which workers contributed to the generation of electricity

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[16] "If the sample of plants is chosen so that each machine in a plant is of the same size and vintage. . . . For such plants the assumption that each machine operates for the same number of hours hot and connected is more plausible than for plants composed of a machine mix of units of different size and vintage where older and smaller machines may only be used for peaking purposes." (Galatin, 1968, p. 41).

can only be determined from questionnaires circulated among the plants in the sample. Inquiries regarding (1) the number of hours each generating unit was connected to load or not connected to load; (2) the number of hours that workers contributed to the generation of electricity; and (3) workers' pay scales should be added into the available questionnaires.

Capital input represents the total cost of machines. Each of these machines is characterized by size and vintage, and the effects of changes in scale and technology on the production process are reflected in the *ex-post* production function for different machines. Therefore, the capital input observed for each plant is assumed to be variable in each vintage category.

Model Specification

Two models are used to investigate the production process in the coal-fired electric power industry. In the first model, the translog cost function is regarded as an exact representation of the "true" function, whereas, in the second model, the "true" function is represented approximately by the translog cost function. Underlying technology is assumed to be linearly homogeneous in the exact representation model. The validity of the assumption is statistically tested in the second (approximate representation) model. The exact model consists of four share equations each with a classical additive disturbance term reflecting errors in cost minimization behavior. The equations are estimated for individual plants in separate vintages using Federal Power Commission data for 1973. In the approximate model, the cost function must be added to the system of (n-1) share equations for efficient estimation (Diewert, 1974; and Christensen and Greene, 1976). Three share equations and a cost function with appropriate disturbance terms are estimated. Finally, the internal consistency[17] assumption between share equations and the cost function is adopted.

Exact model

In this model, a system of four share equations from the multiple-input, multiple-output translog cost function is derived. Major outputs are electricity (Y_1) and collected ash (Y_2), while the major inputs are capital used for generation of electricity (K_1), labor (L), fuel (F), and capital used for the collection of ash (K_2).[18]

The analysis of the multiple-input functional form was originally introduced by Solow (1956). Using two capital inputs and one labor input, he showed that a consistent aggregate capital price or quantity index is possible if the two capital inputs are functionally separable from other inputs (in his case, labor). In this part of the study, capital is stratified into two separate

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[17]Equality of related parameters of share equations and the cost function.

[18]For a detailed explanation of the variables, refer to Appendix B.

inputs K_1 and K_2, where such stratification of the capital input provides for a study of the impact of changes in technology and prices on each vintage. This approach requires a homothetic production function[19] but allows for nonconstant returns to scale. However, cost minimization behavior is assumed. If linear homogeneity in prices holds, the following restrictions are satisfied:[20]

$$\sum_{i=1}^{n} \alpha_i = 1,$$

$$\sum_{i=1}^{n} \beta_i = \sum_{j=1}^{n} \beta_j = 0, \text{ and}$$

$$\sum_{i=1}^{n} \delta_{ik} = 0$$

for i, j = K_1, L, F and K_2 and K = Y_1 and Y_2. The sum of the share equations add up to one, hence (n-1) independent equations are used in the estimation process.

If the translog cost function is regarded as an exact representation of the "true" function, then the above restrictions provide for a test of linear homogeneity of total cost in factor prices, where the underlying technology is linear homogeneous. These restrictions are not, in general, satisfied. Therefore, it is necessary to

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[19] A homothetic function is strictly increasing and is a continuous transformation of another function that is positively homogeneous of degree one (Shephard, 1970).

[20] Linear homogeneity in factor prices, signifies an expansion path through the origin.

empirically verify their existence one-by-one or in combination, over the observed range of prices and quantities. In the exact model, several aspects of the production process, viz. (1) linear homogeneity in factor prices along with the overall separability ($\sigma_{ij} = 1$); (2) overall weak separability (constant σ_{ij}) and linear homogeneity in prices; (3) local nonlinear separability ($\sigma_{ij} = \sigma_{jk}$) between fuel and other inputs; (4) linear separability of fuel and other inputs and finally; (5) separability of the set of inputs from the output set are tested. Appropriate parametric restrictions for the relevant tests are imposed on submodels. Characteristics of these models along with the imposed restrictions are summarized in Table 4. Using the stratified sample of three vintages,[21] the set of four share equations derived from the translog cost function is estimated for all 10 models and each vintage. Estimates of β_{ij}'s, are then used to derive substitution and price elasticities. Following Berndt and Christensen (1973b), the assumption of exact representation of the underlying technology[22] with the following

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[21]The selection of the vintages was based on the starting year of on-line operation and the following assumptions: (1) before the early 1950s, plants of prewar design were operational (V_1); (2) during the 1950s and the early 1960s, labor-saving devices were introduced (V_2), and (3) the 1960s' and early 1970s' designs introduced the new modified generating units combined with the air pollution control devices (V_3). The selection process of V_2 and V_3 is supported by empirical studies (Christensen and Greene, 1976).

[22]Such an assumption implies that the production function exhibits strong separability and self-duality (Burgess, 1975 and Shephard, 1970).

TABLE 4

MODEL IDENTIFICATION FOR THE PROPOSED EMPIRICAL TESTS (Exact Model)

Model	Constraints	Parameter Restrictions
A-I	The least-restricted model	0
B-I	Linear homogeneity in factor prices, symmetry, and strong separability	$\Sigma\alpha_i = 1$, $\beta_{ij} = \beta_{ji} = 0$, $\delta_{iK} = 0$
C-I	Weak separability	$\Sigma\alpha_i = 1$, $\Sigma\beta_{ij} = 0$, $\Sigma\delta_{iK} = 0$
D-I	Nonlinear separability of L and K_1 from F	$\sigma_{LF} = \sigma_{K_1F}$
E-I	Nonlinear separability of L and K_2 from F	$\sigma_{LF} = \sigma_{K_2F}$
F-I	Nonlinear separability of K_1 and K_2 from F	$\sigma_{K_1F} = \sigma_{K_2F}$
G-I	Linear separability between L and F	$\beta_{LF} = 0$
H-I	Linear separability between K_1 and F	$\beta_{K_1F} = 0$
I-I	Linear separability between K_2 and F	$\beta_{K_2F} = 0$
J-I	Homogeneity of production function	$\delta_{iK} = 0$

restrictions is carried out as the set of maintained assumptions.[23] Validity of such assumptions and the constraints associated with them (such as: $\omega_{KK'} = 0$; $\Sigma\gamma_K = 1$, $\Psi_K = 0$ and $\lambda_o = 0$ while $K, K' = 1,\ldots,n$) are statistically verified in the approximate model.

Approximate model

In this model, the underlying technology is assumed to be approximately, rather than exactly, represented. Consequently, the cost function must be added to the system of (n-1) share equations for efficient estimation. Because of the inadequacy of the sample size, a system of three share equations[24] and a cost function is estimated. Major outputs are electricity (Y_1) and collected ash (Y_2), while the major inputs are capital (K), labor (L) and fuel (F).

Internal consistency between the system of share equations and the cost function is hypothesized.[25] Estimates of β_{ij}'s are used to arrive at substitution and price elasticities. It is also assumed that second order differentiability of the cost function

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[23] Inclusion of the cost function to the system of share equations for each vintage creates the degree of freedom problem where $K > n$.

[24] Since $P_{K1} = P_{K2}$, K_1 and K_2 are combined together to account for capital input in the approximate model, to prevent linear dependency between price vectors in the estimation of the cost function.

[25] Appelbaum (1978), in an empirical study of the United States' manufacturing, reports that "the theory performs better with the test for internal consistency" (p. 87).

and internal consistency between share equations and the cost function exist.

Transformation of outputs from factor inputs are influenced by technological change. A vintage variable (v) is introduced in the cost function to represent technological shifts:

$$\begin{aligned} \ln C = \lambda_o &+ \sum_{k=1}^{n} \gamma_K \ln Y_k + 1/2 \sum_{k=1}^{n} \Psi_k (\ln Y_K)^2 \\ &+ \sum_{i=1}^{n} \alpha_i \ln P_i + 1/2 \sum_{i=1}^{n} \beta_{ii} (\ln P_i)^2 \\ &+ \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln P_i \ln P_j + \sum_{i=1}^{n} \sum_{k=1}^{n} \delta_{ik} \ln P_i \ln Y_k \\ &+ \sum_{k=1}^{n} \sum_{k'=1}^{n} \omega_{kk'} \ln Y_k \ln Y_{k'} + \sum_{\ell=1}^{n} \sum_{k=1}^{n} \theta_{\ell k} \ln V_\ell Y_k \\ &+ \sum_{i=1}^{n} \sum_{\ell=1}^{n} \eta_{\ell i} \ln V_\ell \ln P_i + 1/2 \sum_{\ell=1} \phi_{\ell\ell} (\ln V_\ell)^2 \end{aligned} \tag{30}$$

for i, j, k, and $\ell = 1, \ldots, n$ and $K \neq K'$. Because of the specification of the variable (v), the model can provide a test of the existence of an embodied technological change and a test of hypothesis of a Hicksian-neutral technical change.

In the approximate model, several aspects of the production process viz., (1) linear homogeneity in factor prices, (2) functional separability, (3) linear homogeneity in technology functional homotheticity, (4) nonjointness of outputs, (5) linear and nonlinear separability between fuel and other inputs and finally, (6) absence of embodied technological change are tested. Appropriate parametric restrictions for the relevant tests of hypothesis are imposed in 12 submodels. Characteristics of these models along with the imposed restrictions are summarized in Table 5. Estimates of β_{ij}'s are used to derive substitution and price elasticities.

Choice of the Estimation Technique

Random deviations from the cost-minimization behavior should affect all decisions related to factor mix, therefore, the error terms (ε_i and ε_j) are likely to be correlated. Hence, any joint estimation process other than Ordinary Least Square estimation (OLS) would yield more efficient parameter estimates (Humphrey and Moroney, 1975). Application of OLS to each equation separately generates estimates that are unbiased and consistent.

Restrictions such as symmetry and constant returns to scale cannot be imposed on a set of equations estimated by OLS or 2SLS (Berndt and Christensen, 1973b). Since disturbances are positively correlated across equations, a smaller variance can be obtained by the application of a maximum-likelihood estimation or Zellner-efficient techniques.[26]

In the approximate model, joint estimation of the cost function and the share equations will result in more efficient parameter estimates than would be obtained by applying OLS to each equation independently. The Zellner-efficient and the maximum-likelihood estimation techniques can be used to estimate the system if one

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[26]The gain in efficiency will be realized if the Zellner procedure is applied to a set of equations estimated by OLS or 2SLS (Kmenta and Gilbert, 1968).

TABLE 5

MODEL IDENTIFICATION FOR THE PROPOSED EMPIRICAL TESTS (Approximate Model)

Model	Constraints	Parameter Restrictions
A-II	The least-restricted model	0
B-II	Linear homogeneity in factor prices, symmetry, strong separability, and constant returns to scale	$\Sigma\alpha_i = 1$, $\beta_{ij} = \beta_{ji} = 0$, $\delta_{iK} = \delta_{jK} = 0$ $\omega_{KK'} = 0$, $\phi_K = 0$
C-II	Linear homogeneity in factor prices and technology	$\Sigma\alpha_i = 1$, $\Sigma\beta_{ij} = \Sigma\beta_{ji} = 0$, $\Sigma\delta_{iK} = 0$, $\gamma_K = 1$, $\omega_{KK'} = 0$
D-II	Linear homogeneity in factor prices and homotheticity of the cost function	$\Sigma\alpha_i = 1$, $\Sigma\beta_{ij} = \Sigma\beta_{ji} = 0$, $\Sigma\delta_{iK} = 0$
E-II	Nonjointness of outputs, linear homogeneity in factor prices, symmetry, and homotheticity of the functional form	$\Sigma\alpha_i = 1$, $\Sigma\beta_{ij} = \Sigma\beta_{ji} = 0$, $\Sigma\delta_{iK} = 0$, $\omega_{KK'} = 0$
F-II	Hicksian neutral change	$\eta_i = 0$, $\theta_K = 0$
G-II	Nonlinear separability between fuel, labor, & capital	$\sigma_{LF} = \sigma_{KF}$
H-II	Linear separability between capital and fuel	$\beta_{LF} = 0$
I-II	Linear separability between labor and fuel	$\beta_{KF} = 0$
J-II	Linear homogeneity in factor prices, symmetry, and strong separability between outputs and factor prices	$\Sigma\alpha_i = 1$, $\Sigma\beta_{ij} = \Sigma\beta_{ji} = 0$, $\delta_{iK} = 0$, $\beta_{ij} = \beta_{ji}$, $\delta_{iK} = \delta_{Ki}$

TABLE 5 --Continued

Model	Constraints	Parameter Restrictions
K-II	Nonjointness of outputs	$\omega_{KK'} = 0$
L-II	Absence of technological change	$\eta_i = 0,\ \phi = 0,\ \theta_K = 0,\ \xi = 0$

equation is delected. If the Zellner-efficient technique is used the estimates obtained will not be invariant to the equation that is deleted[27] (Burgess, 1975). The maximum-likelihood estimates are independent of the choice of (n-1) selected equations (Barten, 1969). Therefore, the parameters of the cost function are estimated using the maximum-likelihood estimation method (computationally equivalent to the iterative Zellner estimation technique, {Kmanta and Gilbert, 1968}).

Since the production process is an *ex-post* function, it is plausible to assume that the regressor matrix elements are predetermined. Therefore, the choice of the maximum-likelihood estimation technique yields asymptotically efficient estimates of the parameters.[28]

Exact Model[29]

$$N_{K_1} = \alpha_{K_1} + \beta_{K_1K_1} \ln P_{K_1} + \beta_{K_1L} \ln P_L + \delta_{K_1F} \ln P_F + \delta_{K_1Y_1} \ln Y_1 + \delta_{K_1Y_2} \ln Y_2 + \varepsilon_{K_1} \qquad (31)$$

[27] One exception exists where the system is convergence through the iteration process.

[28] To apply the maximum-likelihood estimation process to the data, the computer program and facilities at the University of Wisconsin's computer center were utilized.

[29] Since the share equations are derived by differentiation, they do not contain the error term from the translog cost function.

$$N_L = \alpha_L + \beta_{LK_1} \ln P_{K_1} + \beta_{LL} \ln P_L + \beta_{LF} \ln P_F + \delta_{LY_1} \ln Y_1$$

$$+ \delta_{LY_2} \ln Y_2 + \varepsilon_L \tag{32}$$

$$N_F = \alpha_F + \beta_{FK_1} \ln P_{K_1} + \beta_{FL} \ln P_L + \beta_{FF} \ln P_F + \delta_{FY_1} \ln Y_1$$

$$+ \delta_{FY_2} \ln Y_2 + \varepsilon_F \tag{33}$$

$$N_{K_2} = \alpha_{K_2} + \beta_{K_2K_1} \ln P_{K_1} + \beta_{K_2L} \ln P_L + \beta_{K_2F} \ln P_F$$

$$+ \delta_{K_2Y_1} \ln Y_1 + \delta_{K_2Y_2} \ln Y_2 + \varepsilon_{K_2} \tag{34}$$

Approximate Model

$$N_K = \alpha_K + \beta_{KK} \ln P_K + \beta_{KL} \ln P_L + \beta_{KF} \ln P_F + \delta_{KY_1} \ln Y_1$$

$$+ \delta_{KY_2} \ln Y_2 + \eta_K \ln V + \varepsilon_K \tag{35}$$

$$N_L = \alpha_L + \beta_{LK} \ln P_K + \beta_{LL} \ln P_L + \beta_{LF} \ln P_F + \delta_{LY_1} \ln Y_1$$

$$+ \delta_{LY_2} \ln Y_2 + \eta_L \ln V + \varepsilon_L \tag{36}$$

$$N_F = \alpha_F + \beta_{FK} \ln P_K + \beta_{FL} \ln P_L + \beta_{FF} \ln P_F + \delta_{FY_1} \ln Y_1$$

$$+ \delta_{FY_2} \ln Y_2 + \eta_F \ln V + \varepsilon_F \tag{37}$$

$$
\begin{aligned}
\ln C = {} & \lambda o + \gamma_{Y_1} \ln Y_1 + \gamma_{Y_2} \ln Y_2 + 1/2\ \psi_{Y_1} (\ln Y_1)^2 \\
& + 1/2\ \psi_{Y_2} (\ln Y_2)^2 + \alpha_K \ln P_K + \alpha_L \ln P_L + \alpha_F \ln P_F \\
& + 1/2\ \beta_{KK} (\ln P_K)^2 + \beta_{KL} \ln P_K \ln P_L + \beta_{KF} \ln P_K \ln P_F \\
& + \delta_{KY_1} \ln P_K \ln Y_1 + \delta_{KY_2} \ln P_K \ln Y_2 + \beta_{LK} \ln P_L \ln P_K \\
& + 1/2\ \beta_{FF} (\ln P_F)^2 + \delta_{FY_1} \ln P_F \ln Y_1 + \delta_{FY_2} \ln P_F \ln Y_2 \\
& + 1/2\ \beta_{LL} (\ln P_L)^2 + \beta_{LF} \ln P_L \ln P_F + \delta_{LY_1} \ln P_L \ln Y_1 \\
& + \delta_{LY_2} \ln P_L \ln Y_2 + \beta_{FK} \ln P_F \ln P_K + \beta_{FL} \ln P_F \ln P_L \\
& + \omega_{Y_1 Y_2} \ln Y_1 \ln Y_2 + \theta_{Y_1} \ln V \ln Y_1 + \theta_{Y_2} \ln V \ln Y_2 + \eta_K \ln V \ln P_K \\
& + \eta_L \ln V \ln P_L + \eta_F \ln V \ln P_F + 1/2\ \phi (\ln V)^2 + \xi \ln V \\
& + \varepsilon_C
\end{aligned}
\tag{38}
$$

where the ε's are disturbance terms. It is assumed that:

$E(\varepsilon_i) = 0$, $E(\varepsilon_i \varepsilon_j) = \sigma_{ij}$ K, for i, j = 1,....n, and Xi'Xi's are nonsingular and lim(Xi'Xi)/n exists as n approaches infinity.[30] Since similar parameters and variables appear in each

[30] For further details see Kmenta and Gilbert (1968) and/or any standard econometric textbook. (X represents explanatory variables, i.e., P_i's and Y_K's in the system of share and cost equations.)

equation, it is assumed that disturbances are contemporaneously correlated (Burgess, 1975; Berndt and Christensen, 1973b; and Humphrey and Moroney, 1975).

To analyze change through time, the sample is divided into three subgroups (vintages) and the relevant parameters of the cost equation related to each vintage are estimated in the approximate model.[31]

The maximum likelihood ratio test procedure is used to test the various hypotheses. The likelihood ratio, λ, takes the following form:

$$\lambda = \left(\frac{|\hat{\Sigma}_R|}{|\hat{\Sigma}_U|} \right)^{-1/2}$$

where $|\hat{\Sigma}_U|$ and $|\hat{\Sigma}_R|$ are the value of the determinant of the variance-covariance matrix of the unrestricted and restricted models, respectively, as estimated by the maximum-likelihood estimation technique. Since $-2\ln\lambda$ is distributed asymptotically as Chi-squared (χ^2) with the number of independently imposed restrictions being the relevant degrees of freedom, the test of the hypotheses will be the basis of the following formulation:[32]

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[31]The characterization of technological change is restricted by its specification in the approximate model.

[32]In presentation of parameter estimates, the natural logarithm of the determinant of the variance/covariance matrix is denoted by: Log. det $\hat{\Sigma}$ shown in Appendix F.

$$-2\ln\lambda = n(|\ln\hat{\Sigma}_U| - |\ln\hat{\Sigma}_R|)$$

where n is the number of observation.

CHAPTER IV

EMPIRICAL RESULTS

Using the general specification of the exact model, ten different models for each vintage are estimated. The estimated parameters of the share equations and their asymptotic standard errors for each vintage and model are presented in Appendix F, Tables 16 through 18. The number of observations is 26 for the Vintage I (1941 to 1953) sample, 28 for the Vintage II (1954 to 1961) sample and 26 for the Vintage III (1963 to 1973) sample.

The parameter estimates for the major inputs, labor, fuel and capital, used in the generation of electricity and particulate emission control are denoted by L, F, K_1 and K_2; and the parameter estimates for generated electricity output and collected ash by Y_1 and Y_2, respectively. The results of the statistical tests of hypotheses about the characteristics of the translog cost function in the exact model are summarized in Table 6. Regularity conditions of the cost function, i.e., linear homogeneity in factor prices, symmetry and strong separability, are decisively rejected for all vintages, and are not consistent with the characteristics of the industry's cost function. There is evidence for the acceptance of the nonlinear separability of labor and capital from fuel for Vintages I and II and rejection of such separability for Vintage III.

TABLE 6

TEST STATISTICS FOR RESTRICTED MODELS IN THE EXACT MODEL

Model	Sample Size n	$-2\ln\lambda$	Degrees of Freedom	Critical $\chi^2(.01)$
Vintage I:				
A-I	26	the unrestricted model		
B-I	""	150.65	20	37.6
C-I	""	139.95	5	15.1
D-I	""	2.217	6	16.8
E-I	""	2.282	6	16.8
F-I	""	182.109	6	16.8
G-I	""	178.69	6	16.8
H-I	""	181.62	6	16.8
I-I	""	179.54	6	16.8
J-I	""	158.69	13	27.7
Vintage II:				
A-I	28	the unrestricted model		
B-I	""	92.78	20	37.6
C-I	""	60.11	5	15.1
D-I	""	15.76	6	16.8
E-I	""	15.80	6	16.8
F-I	""	148.11	6	16.8
G-I	""	108.69	5	15.1
H-I	""	100.95	6	16.8
I-I	""	112.89	6	16.8
J-I	""	83.72	13	27.7
Vintage III:				
A-I	26	the unrestricted model		
B-I	""	126.51	20	37.6
C-I	""	101.56	5	15.1
D-I	""	33.50	6	16.8
E-I	""	34.84	6	16.8
F-I	""	157.11	6	16.8
G-I	""	129.23	5	15.1
H-I	""	3.46	6	16.8
I-I	""	3.48	6	16.8
J-I	""	141.09	13	27.7

Nonlinear separability between fuel and two capital inputs is rejected[33] for all vintages. These results imply that in Vintage I and II, capital and labor are separable from fuel. Consequently, a change in the prices of capital and labor should have no effect on the share of fuel in total cost. However, when price of capital is changed independently, the share of fuel will be altered in all vintages.

Linear separability between fuel and capital equipment for both the generation of electricity and particulate emission control is rejected for vintage I and II and accepted for Vintage III. Linear separability between labor and fuel is rejected for all three vintages. These results indicate that the change in the price of capital generates significant effects on the share of fuel for earlier vintages and has no significant effect on the latest vintage. Nevertheless, rejection of linear separability between labor and fuel implies that a unitary elasticity of substitution between fuel and labor is ruled out. Finally, separability between input prices and output is rejected which implies that the underlying production function is not homogeneous.

The parameter estimates for labor (L), fuel (F) and capital (K), generated electricity (Y_1) and collected ash (Y_2) and their asymptotic standard errors for each model are presented in Appendix

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[33]Rejection of the hypothesis implies that σ_{ij} is variable, for derivation of constraints, see Appendix E.

F, Table 19. The number of observation is 80 for the sample of power plants (the approximate model).

The results of the test statistics derived for estimation of the translog cost function in the approximate model, are summarized in Table 7. Homotheticity[34] of the cost function along with the

TABLE 7

TEST STATISTICS FOR RESTRICTED MODELS IN THE APPROXIMATE MODEL

Model	Sample Size n	$-2\ln\lambda$	Degrees of Freedom	Critical $\chi^2(.01)$
A-II	80	the unrestricted model		
B-II	""	157.69	24	43.0
C-II	""	31.20	12	26.2
D-II	""	13.54	3	11.3
E-II	""	15.32	4	13.3
F-II	""	30.64	4	13.3
G-II	""	15.11	4	13.3
H-II	""	23.60	4	13.3
I-II	""	79.60	4	13.3
J-II	""	20.31	6	16.8
K-II	""	7.998	1	6.6
L-II	""	22.18	7	18.5

[34] A homothetic cost function is characterized by unchanging distributive shares with the change in scale (Fuss and McFadden, 1978). Rejection of homotheticity implies that the functional wear separability (imposed by nonlinear constraints) is not a valid assumption (Blackorby, Primont, and Russel, 1974).

regularity conditions of the cost function are rejected. These results suggest that the industry's production structure cannot be adequately represented by a homothetic cost function. Nonlinear and linear separability between capital, labor and fuel are rejected which implies that changes in the price of labor and capital have an effect on the share of fuel in total cost. Furthermore, separability of outputs is rejected which implies that outputs are related, and in fact are positively related since their interaction coefficient is positive.

Finally, both absence and Hicksian neutrality of technological change are rejected, implying that technical change is not "output augmenting" and "factor saving" at equal rates.[35] Nevertheless, the model provides statistical evidence for the presence of embodied technological change. These results conform with the results of Atkinson and Halvorsen (1976).

A general review of the models and related test statistics reveals that the hypotheses or assumptions incorporated in different models may be valid for one vintage but do not hold for another. It is obvious that the traditional linear and log-linear models (i.e., CES) are not appropriate for representation of production relationships in the United States coal-fired electric power industry. Specifically, statistical evidence, drawn from both model specifications of the regularity conditions, suggests that unitary elasticity of substitution and/or strong separability do

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[35]This result is not in conflict with the characteristics of a nonhomothetic function.

not appear to be valid assumptions in representations of the production structure of the industry. Since homotheticity of the cost function is rejected, a homothetic cost function is also suspect as a representation of the production structure of the industry. This result is in conflict with Atkinson and Halvorsen's (1976) general findings for the United States steam electric power plants, and Komiya's (1962) argument which favors the modeling of fixed coefficient production structures.

Although linear homogeneity in factor prices and homotheticity of the functional forms are in general rejected, their marginal rejection does not provide strong evidence against the cost minimization behavior. In addition to regulatory constraints, increases in the price of capital in the early 1970's suggest that use of unnecessary capital was scant. Therefore, the cost minimization assumption for the firms at the plant level in 1973 is more plausible than any other *a priori* assumption on entrepreneurial behavior. Deviations of the results from the conditions are mainly caused by poor quality of the data and the regulatory pressures that affect production decisions in electric power generation.

In order to estimate substitution and price elasticities, appropriate models based on the value of the test statistic (λ) are selected. In the exact model specification, model D-I is chosen for the derivation of such elasticities for Vintages I (Table 16) and II (Table 17) and model H-I is used for Vintage III (Table 18). Finally, parameter estimates from model A-II, as shown in

Table 19, are used to derive the substitution and price elasticities of the approximate model.

Estimated Elasticities

Estimated elasticities of price and input substitution, evaluated at the point of approximation,[36] are presented in Tables 8 and 9 for each vintage (in the exact model). Own price and substitution elasticities should be negative and the cross-price elasticities should be positive if major inputs are substitutes.

In three series of estimated substitution and price elasticities (Tables 8 and 9) for all vintages, own substitution elasticities (i.e., σ_{ii}) show the expected relationship.[37] The estimated own-price elasticities (η_{ii}) are negative, implying that the corresponding demand schedules are downward sloping.

Substitution possibilities for vintage I and Vintage III are the same with the exception of fuel and labor elasticities. While a substitution relationship is observed for earlier vintages, a complimentary relationship is observed in the latest vintage. This result signifies the existence of a labor-saving technology that has been gradually introduced within the industry. Substitution possibilities between capital equipment for generation of electricity

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[36] The approximation point represents the geometric mean of the sample.

[37] The positive sign of $\sigma_{K_1K_1}$ in Vintage II is somewhat disturbing although its magnitude is not significant.

TABLE 8

ESTIMATED ELASTICITIES OF SUBSTITUTION
(EXACT MODEL)

	Vintage (Model)		
	I (D-I)	II (D-I)	III (H-I)
$\sigma_{K_1K_1}$	- 5.36001	0.32528	- 2.84152
σ_{K_1L}	- 0.03296	1.04930	- 0.00711
σ_{K_1F}	0.25318	0.93686	1.00000
$\sigma_{K_1K_2}$	-18.99252	53.77962	-12.57690
σ_{LK_1}	- 0.03296	1.04930	- 0.00711
σ_{LL}	- 2.46780	-3.90621	- 2.49772
σ_{LF}	0.25318	0.06331	- 0.07742
σ_{LK_2}	-11.51371	1.67511	-20.64356
σ_{FK_1}	0.25318	0.93686	1.00000
σ_{FL}	0.45072	0.06331	- 0.07742
σ_{FF}	- 0.33926	-0.07361	- 0.23168
σ_{FK_2}	- 8.04733	0.13528	- 3.49150
$\sigma_{K_2K_1}$	- 8.34404	1.12078	-12.57690
σ_{K_2L}	-11.51371	1.67511	-20.64350
σ_{K_2F}	- 8.04733	0.13528	- 3.49150
$\sigma_{K_2K_2}$	-168.98687	-59.36540	-359.75781

TABLE 9

ESTIMATED PRICE ELASTICITIES OF DEMAND
(EXACT MODEL)

	Vintage (Model)		
	I (D-I)	II (D-I)	III (H-I)
$\eta_{K_1K_1}$	-1.14341	0.07182	-0.88527
η_{K_1L}	-0.00703	0.23169	-0.00222
η_{K_1F}	0.05401	0.20680	0.31155
$\eta_{K_1K_2}$	-4.05154	11.87486	-3.91832
η_{LK_1}	-0.00564	0.14555	-0.00085
η_{LL}	-0.42210	-0.54185	-0.29876
η_{LF}	0.04330	0.00878	-0.00926
η_{LK_2}	-1.96934	0.23237	-2.46922
η_{FK_1}	0.14587	0.56846	0.53937
η_{FL}	0.25969	0.03841	-0.04176
η_{FF}	-0.19547	-0.04466	-0.12496
η_{FK_2}	-4.63652	0.08209	-1.88321
$\eta_{K_2K_1}$	-0.14693	0.01807	-0.18233
η_{K_2L}	-0.20274	0.02701	-0.29927
η_{K_2F}	-0.14171	0.00218	-0.05062
$\eta_{K_2K_2}$	-2.97569	-0.95721	-5.21537

and fuel exist for all vintages. Complementarity between labor and both types of capital is observed in Vintage I and III which implies that labor and capital move together in the production of electricity. In Vintage II plants, substitution relationship, and in Vintage I and III plants, a complementary relationship between ash collection capital and other inputs is observed. This result signifies the parallel movements of respective inputs in production of electricity. The demand for this capital shows an inelastic response to the change in prices of other inputs. This is consistent with the hypothesis that equipment used for air pollution control can be eliminated with no effect on production efficiency.

An increase in the price of any input is most likely to be accompanied by a decline in its relative share. The values of the estimates for individual plants are similar to the elasticities evaluated at the mean of each sample. There are few extreme values (i.e., elasticities between labor and fuel and labor capital equipment for generation of electricity in Vintage III). A complementary relationship between fuel, labor and capital equipment for particulate emission control is observed for every plant in Vintage I and III.

Substitution and price elasticities for the approximate model are presented in Table 10. The substitution elasticities between inputs have the appropriate sign and reveal the expected complementary relationship within each factor for all inputs. Own-price elasticities are negative which correspond to negatively sloped demand schedules.

TABLE 10

ESTIMATED ELASTICITIES OF SUBSTITUTION AND THE PRICE ELASTICITIES OF DEMAND (Approximate Model)

σ_{KK}	-0.39324	η_{KK}	-0.10904
σ_{KL}	0.72926	η_{KL}	0.20190
σ_{KF}	0.32513	η_{KF}	0.09002
σ_{LK}	0.49185	η_{LK}	0.07034
σ_{LL}	-3.94812	η_{LL}	-0.56464
σ_{LF}	0.53661	η_{LF}	0.07674
σ_{FK}	0.04681	η_{FK}	0.02691
σ_{FL}	0.63537	η_{FL}	0.36529
σ_{FF}	-0.31428	η_{FF}	-0.18068

Substitution between all pairs of inputs exists. The magnitude of substitution ranges from 0.047 for σ_{FK} to 0.730 for σ_{KL}. At the plant level, capital and fuel can be substituted for labor with more flexibility than any other combination.

An inelastic response of capital, labor and fuel to a change in the price of capital, wage rate and price of coal is observed. While these findings indicate that limited substitution over all vintages prevails, the observed complementarity relationship for each vintage between labor, fuel, capital for generation of electricity, and for capital used for particulate emission control in Vintage I and III, provide sufficient evidence of misallocation of resources in the use of particulate emission control devices. It is clear that imposition of more and more limiting air quality standards would generate economic incentives for a shift away from coal to other cleaner fuels if such were permitted.[38] Furthermore, there is a rather consistent negative relationship between electricity generation and the use of capital for particulate emission control as expressed in the share equation estimates (see Appendix F, Tables 16 and 17). The limited substitution findings are consistent with those of Nerlove (1963) and Christensen and Greene (1976). In previous empirical studies of the production structure of the United States' electric power industry (1955 and 1970 data), it has been reported that significant substitution possibilities occur within the industry at the firm level. The demand price elasticity estimates of this study suggest that changes in the price of inputs result in a relatively inelastic response in the share of inputs. Christensen and Greene (1976) report that the share of fuel is completely inelastic.

To provide a basis of comparison, Nerlove and Christensen and Greene's estimates of substitution and price elasticities, along with the estimates drawn from Table 10, are presented in Table 11. Nerlove

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[38]The sample used for this empirical study only includes plants in which coal provides the significant source of energy. As a result, the concept of interfuel substitution is not discussed.

TABLE 11

ESTIMATED ELASTICITIES OF SUBSTITUTION AND PRICE ELASTICITIES

Elasticities of Substitution	Labor-Capital	Capital-Fuel	Labor-Fuel
Nerlove (1955 data)	0.411	0.223	0.658
Christensen-Greene (1970 data)	0.639	0.218	0.163
This study (1973 data)	0.492	0.325	0.537
Price Elasticities	**Capital**	**Labor**	**Fuel**
Nerlove (1955 data)	-0.159	-0.499	-0.193
Christensen-Greene (1970 data)	-0.238	-0.229	-0.081
This study (1973 data)	-0.109	-0.565	-0.181

estimates are surprisingly close to the estimates of the present study, which suggests the same pattern for direct substitution between factor inputs in response to price changes specific to the coal-fired electric power industry.[39]

Economies of Scale

Most engineering estimates predict that economies of scale in the generation of electricity will persist indefinitely. Christensen

[39] Nerlove's results were for firms rather than plants.

and Greene (1976), show that the majority of the United States electric power was produced by firms which are operating in the flat portion of the average cost curve. Johnston (1960) and Nerlove (1963), found that scale economies were exhausted for firms of relatively medium size. In order to address issues of this nature, a measure of economies of scale for the coal-fired electric power industry for 1973 is derived.

Economies of scale is defined as the relative increase in output resulting from a proportional increase in all inputs. Such a relationship is identified by the relationship between total cost and output along the expansion path, defined by the elasticity of total cost with respect to output:

$$\frac{\partial C}{\partial Y} \cdot \frac{Y}{C} = \frac{1}{\dfrac{\sum_{i=1}^{n} MP_i X_i}{y} \Big/ Y} = \frac{\partial \ln C}{\partial \ln Y} \tag{39}$$

where C and Y represent total cost and level of salable output, and MP_i and X_i are marginal product and level of the ith input, respectively. Economies of scale, ES, can then be defined as unity minus the elasticity of total cost with respect to output (Christensen and Greene, 1976), i.e.,

$$ES = 1 - \frac{\partial \ln C}{\partial \ln Y} \ , \tag{40}$$

where ES is the degree of economies of scale, C is the total cost, and Y is the level of production. ES is positive when the percentage change in total cost with respect to output is less than one, equal to zero when a proportional change in output is exactly equal to proportional change in total cost, and is negative when the proportional change in output results in more than a proportional change in total cost. Positive ES numbers represent economies of scale and negative numbers imply diseconomies of scale. The formula for the economies of scale derived from the translog cost function (30) is as follows:

$$ES = 1 - \{(\gamma_K + \Psi_K) + \sum_{i=1}^{n} \delta_K \ln P_i + \sum_{K'=1}^{n} \omega_{KK'} \ln Y_{K'}$$
$$+ \sum_{K=1}^{n} \theta_{\ell K} \ln V_\ell\} \qquad (41)$$

Scale economies can be estimated by the evaluation of Equation (36) at the observed level of output and factor prices. Economies of scale is examined for each vintage for plants which produced the highest, average and lowest level of output (million kwh). Estimates for scale economies for each vintage are presented in Table 12. The variation of economies of scale with output confirms, in general, that scale economies decline as output increases.

Economies of scale for all vintages and the range of output levels is observed. The rate of change of scale economies in the earliest vintage (1941 to 1953) plants, is higher than that of Vintage III (1963 to 1973) plants. This implies that, for an equi-proportional change in output, the rate of increase in total cost for plants of the earliest vintage will be relatively lower than that of latest vintage.

TABLE 12

ESTIMATED ECONOMIES OF SCALE FOR VARIOUS VINTAGES

Output (million kwh)		Scale Economies
Vintage I		
(Low)	174	.35876
(Medium)	1235	.32070
(High)	9941	.15197
Vintage II		
(Low)	245	.16575
(Medium)	2111	.26958
(High)	12945	.18464
Vintage III		
(Low)	1061	.27142
(Medium)	2303	.24721
(High)	9469	.16908

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The general framework used in this study appears to be useful for the analysis of the underlying production structure of the coal-fired electric power industry. Relevant information about factors that determine production is obtained from the model and is contained in the substitution and price demand elasticities. The framework is specifically useful in the analysis of the price change impacts on total expenditure or input mix. Tests of hypotheses of certain regularity conditions of the cost function, as implied by neoclassical theory were performed. The maximum-likelihood ratio test was used to empirically test the validity of various restrictions on the production structure for the United States' coal-fired electric power industry. The test is dependent on the value of the determinant of the variance-covariance matrices of both restricted and unrestricted (least-restricted) models. Therefore, the strength of the test is influenced by the parameter estimates and the asymptotic standard errors. Although an asymptotic test of each estimated parameter in various models is not available, comparison of each coefficient with its asymptotic standard error generates a criterion for which the strength of empirical estimates can be evaluated. In some of the models, several of the asymptotic errors are large relative to the estimated coefficients. Nevertheless, the empirical results of this study show evidence that traditional models, with the *a priori* linear and log-linear characterization and the restrictive substitution elasticities derived therefrom, are suspect as adequate representations of the production structure of the United States' coal-fired electric power industry.

Estimation of a translog cost function makes it possible to calculate the extent and magnitude of input substitution in the coal-fired electric power industry without imposing *a priori* constraints on the values of elasticities. Moreover, the use of a flexible functional form makes it possible to test a number of hypotheses concerning other characteristics of the production process.

For all vintages, an increase in price of capital will reduce the share of capital for ash collection equipment, and an increase in the price of labor and fuel results in a decline in the share of labor and fuel, respectively (Tables 9 and 10).

The Clean Air Act Amendment of 1977 calls for a 0.3 pound particulate emission ceiling per million BTU. Such a standard may preclude the use of electrostatic precipitators, i.e., a major capital investment in particulate emission control. The Department of Energy has suggested a higher level of particulate emission control in the range of 0.05 to 0.08 pound per million BTU, which would not preclude electrostatic precipitators (see Table 3).

Estimated price elasticities for labor, fuel, and capital equipment for generation of electricity for Vintage I and III plants are very close to zero, which implies that the shares of fuel and capital equipment used in generation of electricity do not change significantly in response to a change in the wage rate. This conforms with the results of the nonlinear separability test between labor, capital for generation of electricity and fuel in the exact model specification discussed earlier.

When a substitution possibility between a pair of inputs exists, the relationship between σ_{ij} and σ_{Kj} determines the direction of substitution in response to a price change. Identification of these directions provides an important tool for analyzing proposals to restructure the electric power industry. In Table 10, the substitution elasticities of factor inputs for the industry were displayed. All σ_{ij}'s are positive with their values ranging from 0.04681 to 0.72926, implying limited substitutability. These results suggest that increases in the price of labor, capital, and fuel shift expenditure from fuel to capital, fuel to labor, and capital to labor, respectively, but again, such substitution is limited. Substitution may prove to be economically infeasible, but an appropriate change of relative prices can very well change the consequences in favor of substitution.

Technological change appears to have induced a labor-saving trend since 1941 (Table 13). The share of labor declined steadily from 17 percent in the 1941 to 1953 vintage to 14 percent in the 1954 to 1961 vintage and, finally, to 12 percent in the 1963 to 1973 vintage.

Vintage III shows a reduction in the use of fuel and a significant increase in the share of capital. This is consistent

TABLE 13

AVERAGE SHARE OF THE INPUTS

Exact Model	Vintage I	Vintage II	Vintage III
NK_1	0.213	0.221	0.312
NL	0.171	0.139	0.120
NF	0.576	0.607	0.539
NK_2	0.018	0.016	0.015

Approximate Model	All Vintages Combined
NK	0.277
NL	0.143
NF	0.575

with Komiya's findings on the effect of technological change (Komiya, 1962). These findings imply that the increase of capital used for generation of electricity is parallel to the introduction of more labor and fuel-efficient technology in the last vintage. The share of capital used for particulate emission control was expected to rise, but, on the contrary, it declined from 1.8 percent in the 1941-1953 vintage to 1.4 percent in the 1963-1973 vintage. This is due to the availability of a more efficient and less expensive ash collection technology in the later vintages.

Variation of economies of scale shown in this study confirms the expectation that economies decline as the firm size increases. Contrary to the findings of Christensen and Greene (1976), the empirical results indicate that the majority of plants operate on the portion of the cost curve where economies of scale are present.

Conclusions

Analysis of the cross-section data, through a more flexible characterization of the coal-fired electric power industry's cost function, generates several important conclusions. First, the traditional linear and log-linear representations are rejected by the use of the maximum-likelihood ratio test, which suggests that models with constant elasticity of substitution (i.e., CES, Cobb-Douglas, and separable functions) may not appropriately represent the production structure of the United States' coal-fired electric power industry. Based on these empirical findings, a model which permits nonunitary elasticity of substitution and nonhomotheticity[40] appears to be a more adequate representation of the industry. Therefore, the choice and the direction of the policy actions depend on the reliability of the underlying production estimates.

Substitution among fuel, labor, and capital inputs can be encouraged by policy actions. Knowledge of the substitution and price elasticities are essential for assessing the impact of such policy

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[40] A nonhomothetic function is characterized by a variable factor intensity in response to a scale change.

instruments. Imposition of a tax on coal and/or more rigid safety standards for coal mining will undoubtedly raise the price of coal. In the presence of such a policy, plants in Vintage III will adjust by substituting away from fuel and increasing the share of capital equipment for electricity generation. That is, utilities will decide to invest in more turbogenerators of newer vintage (and efficiency), or obtain fuel of higher BTU content to maintain given levels of electricity generation. There is evidence from this study that a complementary relationship exists between fuel and particulate control capital, and, in the most recent vintage, they are found to be separable. That is, particulate control capital has been imposed irrespective of fuel and fuel price changes. That imposition is perceived to be in place particularly in the more recent time period. Recent laws will accentuate that relationship.

There are probably many elements that influenced these empirical results. Several assumptions were used as the set of maintained hypotheses, which require further empirical verification such as Appelbaum (1978) notes: ". . . one should be careful in his interpretation of the empirical results obtained on the basis of the application of neoclassical production theory" (p. 102). Some hypotheses were rejected, and some or all of the neoclassical maintained hypotheses might have been the reason for rejection. Inadequacy of data, *a priori* assumptions, model specification limitation, some weaknesses in the estimates, and inadequacy of the order of local approximation in the functional form (second order) suggest that the results should be carefully interpreted and interpreted with some degree of caution.

Empirical results found in this study contradict with some widely held beliefs about the production structure of the electric power industry and have potentially useful implications for private and public use, although more conclusive evidence is needed. The contents and quality of the present study can be further improved. Transformation between outputs and characterization of technological change could have been appropriately analyzed had revenue data on a plant-by-plant basis been available. A more appropriate analysis of the air pollution control in the production process should include the sulfur-oxide emission input in the empirical study. However, because of weaknesses in the data and in the performance of the model, further work is required to confirm the results. In further research inclusion of other air pollution control elements in a flexible profit function model specification for the coal-fired electric power industry is strongly recommended. Such specification should consider other specific aspects of technical change and appropriate economic inferences (i.e., elasticity of transformation) that were not directly accounted for in the course of this study. The model used was a more flexible specification than those used in previous studies, however, some characterizations of the production process have not been captured by its use. A complete test of fixed proportions overall was not able to be performed, although the evidence suggests limited input substitution. A nonhomothetic fixed proportions function might be of help in this respect if one was to be estimated and compared with the translog, or another flexible model such as the generalized Leontief (Diewert, 1974).

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APPENDICES

Appendix A

Explanation of Variables Used in This Study

I. Explanation of variables which were directly used in the estimation process:

Outputs

Y_1	Net generation in million kilowatt hours
Y_2	Collected ash (particulate) in 1,000 tons

Inputs

K_1	Capital one--the equipment and material cost for generation of electricity in dollars
L	Labor--annual average number of employees
F	Fuel--annual coal consumption in million BTU
K_2	Capital two--the equipment and material cost for collection of ash in dollars

Prices

P_Y	Total production cost per million kilowatt hours of generated electricity in dollars
P_{K_1}, P_{K_2}	Price of capital equipment used in generation of electricity and collection of ash in dollars
P_L	Annual cost of labor in dollars
P_F	Cost of fuel per million BTU in dollars
V	Capital investment in 1,000 dollars multiplied by an appropriate index

II. Explanation of variables which were indirectly used in the estimation process:

MP	Total cost of mechanical precipitator in dollars
ESP	Total cost of electrostatic precipitator in dollars
Stack	Total cost of high stack in dollars
E	Total cost of equipment used in generation of electricity and particulate emission control in 1,000 dollars
EMNO	Total number of precipitators in each plant

TP	Total cost of labor and parts used in operation and maintenance in 1,000 dollars
F_{11}	Average BTU per net kilowatt hour of generated electricity
P_{FF}	Price of fuel per million BTU in cents
T	Total ash collection, dispersion, and other related expenditures in 1,000 dollars (labor and parts)
S	Sale price of the collected ash in 1,000 dollars "by-product sale"

Appendix B

Data Measurements

The multiple-input, multiple-output model examined in this dissertation included variables that were directly used in the estimation process. To arrive at such values that would account for capital, labor, fuel as inputs and electricity, and collected ash as outputs, the following procedures were followed:[41]

I. Output variables:

<u>Output one</u> (Y_1):

Data for net generation of electricity in million kilowatt hours as reported by Federal Power Commission (FPC, 1976b) for each plant were directly used in the model.

<u>Output two</u> (Y_2):

Data for collected ash as reported by FPC (1976a) for each plant were directly used in the model.

II. Input variables:

<u>Capital input for generation of electricity</u> (K_1):

To arrive at K_1 (capital input in dollars), the equipment cost for generation of electricity, the following adjustments were made:

$$E_2 = \text{stack} + MP + ESP$$

$$E_1 = E \cdot 1{,}000 - E_2$$

$$TA = T - S$$

$$TE = TP - TA$$

E_2 represents the total cost of equipment used in particulate emission control in dollars. E_1 represents total cost of equipment used in generation of electricity and particulate emission control in dollars. TA accounts for the net operation

[41]See Appendix A for explanation of variables and Appendix C for actual data.

and maintenance cost of particulate emission control. TE stands for the operation and maintenance cost of generation of electricity.

The share of parts and labor used in maintenance are included in the operation and maintenance cost data. In order to account for the capital input share of the parts used in operation, a net 11 percent share was included in the adjustment as follows:

$$K_1 = E \cdot P_{K_1} + 0.11 \cdot 1{,}000 \cdot TE$$

The process through which the 11 percent figure was determined is discussed at length in what follows.

Labor input (L):

Annual average number of employee data per plant as reported by Federal Power Commission (FPC, 1976b) were directly used in the model.

Fuel input (F):

To arrive at F, defined as the annual coal consumption per plant in million BTU in the model, the following adjustments were made:

$$F = F_{11} \cdot 10^6 \cdot Y_1/10^6 = F_{11} \cdot Y_1$$

where F_{11}[42] represents the average BTU per net kilowatt hour of generated electricity and Y_1 accounts for generated electricity in million kilowatt hours.

Capital input for particulate emission control (K_2):[43]

To arrive at K_2 (capital input in dollars), the equipment cost for particulate emission control, the following adjustments

[42] Note, F_{11} is reported by FPC (1976b) as a sum total without the introduction of allowance for the fact that machines were or were not connected to load during the consumption process.

[43] See Appendix A for explanation of variables and Appendix C for actual data.

were made:

$$P_{K_1} = P_{K_2} \quad \text{(since both represent the price of capital)}$$

$$E_2 = \text{stack} + MP + ESP$$

$$TA = T - S$$

where E_2 and TA are the same as were used in the calculation of K_1; therefore,

$$K_2 = E_2 \cdot P_{K_2} + 0.11 \cdot TA \cdot 1{,}000$$

The process through which the 11 percent figure was determined is discussed in length in "price of labor (P_L)".

III. Vector of prices:

Price of capital (P_{K_1}, P_{K_2}):[44]

As a proxy of the price of capital, the bond rate of utilities as of 1973 (Hanson, 1974) is used. The actual price of capital may be underestimated since the equity cost is not accounted for, but it still serves as a good relative measure of cost between firms because:

a) it reflects money market activity; and

b) the Moody's Investment Service has scrutinized the companies and analyzed their risk in assigning an investment rating. These ratings influence the debt cost thus used and likely influence the equity cost in much the same way.

Price of labor (P_L)

The FPC reports provide two figures for plant labor expenditures, viz., labor cost in operation and in maintenance, where the latter element includes the labor, supplies, and expenses for maintenance. In order to account for the share of capital

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[44] See Appendix A for explanation of variables and Appendix C for actual data.

input used as supplies and expenses in maintenance, a random sample of 10 coal-fired electric power plants of 1947 published data as shown in Table 14 was taken, and an average supplies and expenses share was calculated.[45]

On average, the supplies share of cost are equal to 11 percent of the labor expenses in operation. Using the same flat percentage, the maintenance and supervision and engineering figures as reporete by FPC are adjusted downward by 11 percent. Following is an adjustment which will yield the annual price of labor in dollars:

$$PL = 0.89 \cdot TP \cdot 1{,}000/L \quad \$/\text{year}$$

Price of fuel (P_F):[46]

Cost of fuel data per million BTU in cents as reported by the Federal Power Commission (FPC, 1976b) were adjusted in dollars per million BTU and directly used in the model.

$$P_F = P_{FF}/100 \qquad \$ \text{ per million BTU}$$

Price of output (production cost per million KWH) (P_Y):

The total production cost data per million kilowatt hours of generated electricity in dollars was generated through the following adjustment procedure:

$$P_Y = (TP \cdot 1{,}000)/Y_1 + P_F \cdot F + (K_1 + K_2)/Y_1$$

where P_Y is the total production cost per million KWH in dollars.

[45] FPC reports for 1938-47 separate the labor cost from supplies and expenses. The total labor cost on supplies and expenses does not cover a big share of the labor input; hence, it is plausible to assume that the ratio of parts to labor in operation and maintenance are the same and have remained constant since 1947.

[46] See Appendix A for explanation of variables and Appendix C for actual data.

TABLE 14

A RANDOM SAMPLE OF 10 COAL-FIRED POWER PLANTS (1947)

Plants	Capacity MW	Operation Labor Expenses/ $1,000	Operation Supplies and Expenses/ $1,000
1. Huntley (NY)	240.0	522	31
2. Gilbert (NJ)	55.0	122	13
3. Springdale (PA)	290.0	787	83
4. Chesterfield (VA)	50.0	140	30
5. Riverside (MD)	120.0	336	28
6. Cahokia (IL)	300.0	845	90
7. West Port (MD)	247.6	1,010	66
8. Ashtabula (OH)	200.0	446	103
9. Parr (SC)	72.5	142	33
10. Mad River (OH)	40.0	136	10

SOURCE: FPC (1949).

IV. Vintage variable (V):

The variable vintage[47] (V) represents the state of technology based on the design era (period) and the capital investment in each plant. The estimation procedure presented in the approximate model tests for the embodied technological change. An arbitrary equidistance indexing procedure was adopted to the vector of megawatt capacity to arrive at the "V" vector.

For the samples 1 through 26 (Vintage I), the total capital investment[48] was multiplied by "1", 27 through 54 (Vintage II) by "2", and 55 through 80 (Vintage III) by "3".

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[47] For more detailed information, refer to the data section.

[48] For the actual data, see Appendix C.

Appendix C

Data

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE I

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	Y1*	Y2**	K1#	L*	F#	F11#	PY#
1	GULF POWER CO.	SCHOLZ.	SNEADS.	FLA.	98.0	506	23	929949	54	6019704	11899	10431
2	ELECTRIC ENERGY INC.	JOPPA.	JOPPA.	ILL.	1100.3	7571	339	5459486	325	76025974	10042	5531
3	KENTUCKY UTILITIES CO.	GREEN RIVER.	S.CARROLTON.	KY.	263.6	174	53	2433363	90	2062608	11875	30103
4	THE POTOMAC EDISON CO.	SMITH.R.PAUL.	WILLIAMSPORT	MD.	110.5	497	23	1271743	53	5587663	11236	9747
5	CONSUMERS POWER CO.	WHITING,J.R.	ERIE.	MICH	325.0	2212	103	2550706	119	21925573	9913	8532
6	DETROIT PUBLIC LIGHTING COMMISSION.	MISTERSKY.	DETROIT.	MICH	174.0	715	31	1808929	156	8026693	11234	11462
7	NEW YORK STATE ELEC.&.GAS CORP.	HICKLING.	EAST CORNING.	N.Y.	86.5	495	129	810944	57	7534281	15230	8786
8	NIAGARA-MOHAWK POWER CORP.	DUNKIRK.	DUNKIRK.	N.Y.	628.0	3589	215	6179496	157	36099739	10059	8613
9	DUKE POWER CO.	DAN RIVER.	DRAPER.	N.C.	290.0	1992	109	1989119	98	20722687	10404	6933
10	BLACK HILLS POWER & LIGT CO.	OSAGE.	OSAGE.	WYO.	34.5	251	15	262917	29	3420551	13644	5563
11	TENNESSEE VALLEY AUTHORITY.	JOHNSONVILLE	JOHNSONVILLE.	TENN	1485.2	6666	320	10736472	402	70056507	10510	6587
12	TENNESSEE VALLEY AUTHORITY.	SHAWNEE.	PADUCAH.	KY.	1750.0	9941	689	13217875	489	98611744	9920	5375
13	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"A".	STEVENSON.	ALA.	853.0	4017	233	5664752	251	43338035	10790	6904
14	MONONGAHELA POWER CO.	ALBRIGHT.	ALBRIGHT.	W.VA	278.3	2018	124	2333971	87	22814621	11305	5651
15	MONONGAHELA POWER CO.	RIVERSVILLE.	RIVERSVILLE.	W.VA	109.8	898	71	1213168	96	12233484	13620	7847
16	MONONGAHELA POWER CO.	WILLOW ISLAND.	ST.MARY'S.	W.VA	215.0	1435	92	2294287	73	15387851	10721	6487
17	INDIANAPOLIS POWER & LIGHT CO.	PRITCHARD,H.T.	CENTER TOWN.	IND.	396.4	1245	57	3150557	105	14406158	11574	8457
18	MINNESOTA POWER & LIGHT CO.	AURORA.	AURORA.	MINN	116.1	452	35	1474177	47	5893469	13030	11659
19	OHIO EDISON CO.	BURGER,R.E.	DILLS BOTTOM.	OHIO	653.6	2851	188	4931686	246	31644359	11099	8312
20	OHIO EDISON CO.	GORGE.	AKRON.	OHIO	100.6	479	40	685558	80	5824302	12172	9191
21	PENNSYLVANIA POWER & LIGHT CO.	SUNBURY.	SUNBURY.	PA.	409.8	2653	228	3938240	191	32017611	12068	8166
22	WEST PENN POWER CO.	MILESBURG.	MILESBURG.	PA.	46.0	274	19	496221	28	3532646	12907	8624
23	WEST PENN POWER CO.	SPRINGDALE.	SPRINGDALE.	PA.	215.4	1171	51	1965334	108	13196992	11266	8055
24	WEST PENN POWER CO.	MITCHELL.	COURTNEY.	PA.	448.7	2570	127	3830552	96	26955104	10490	6618
25	DAIRYLAND POWER COOPERATIVE.	ALMA.	ALMA.	WISC	187.8	1235	99	1763403	71	12944781	10485	8735
26	DAIRYLAND POWER COOPERATIVE.	STONEMAN.	CASSVILLE.	WISC	51.8	222	22	501289	41	2771630	12513	12145

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE I

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	EMNO**	TP*	E2#	PFF*	T*	S**	YR*
1	GULF POWER CO.	SCHOLZ.	SNEADS.	FLA.	98.0	2.0	1028	164100	54.8	71.80	0.00	53
2	ELECTRIC ENERGY INC.	JOPPA.	JOPPA.	ILL.	1100.3	12.0	6957	13460000	38.1	66.90	0.80	53
3	KENTUCKY UTILITIES CO.	GREEN RIVER.	S.CARROLTON.	KY.	263.6	6.0	1872	2057720	35.3	63.00	0.00	50
4	THE POTOMAC EDISON CO.	SMITH.R.PAUL.	WILLIAMSPORT	MD.	110.5	6.0	804	1833000	46.3	252.90	0.00	47
5	CONSUMERS POWER CO.	WHITING.J.R.	ERIE.	MICH	325.0	5.0	2426	4865500	61.4	44.00	0.00	52
6	DETROIT PUBLIC LIGHTING COMMISSION.	MISTERSKY.	DETROIT.	MICH	174.0	2.0	1854	234700	56.1	42.78	0.00	41
7	NEW YORK STATE ELEC.&.GAS CORP.	HICKLING.	EAST CORNING.	N.Y.	86.5	6.0	1020	163600	33.0	139.70	0.00	48
8	NIAGARA-MOHAWK POWER CORP.	DUNKIRK.	DUNKIRK.	N.Y.	628.0	4.0	4101	19517800	52.7	10.66	0.00	50
9	DUKE POWER CO.	DAN RIVER.	DRAPER.	N.C.	290.0	4.0	1315	3843980	49.2	32.00	0.00	49
10	BLACK HILLS POWER & LIGT CO.	OSAGE.	OSAGE.	WYO.	34.5	3.0	364	33800	22.3	26.80	0.00	48
11	TENNESSEE VALLEY AUTHORITY.	JOHNSONVILLE	JOHNSONVILLE.	TENN	1485.2	10.0	6655	1091000	37.7	283.00	0.00	51
12	TENNESSEE VALLEY AUTHORITY.	SHAWNEE.	PADUCAH.	KY.	1750.0	4.0	7439	10257800	32.4	421.00	0.00	53
13	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"A".	STEVENSON.	ALA.	853.0	6.0	5242	745200	38.6	273.00	0.00	52
14	MONONGAHELA POWER CO.	ALBRIGHT.	ALBRIGHT.	W.VA	278.3	3.0	1472	1299000	32.8	141.00	0.40	52
15	MONONGAHELA POWER CO.	RIVERSVILLE.	RIVERSVILLE.	W.VA	109.8	4.0	1739	491000	33.1	92.90	0.00	43
16	MONONGAHELA POWER CO.	WILLOW ISLAND.	ST.MARY'S.	W.VA	215.0	2.0	1696	693000	34.2	75.10	0.50	49
17	INDIANAPOLIS POWER & LIGHT CO.	PRITCHARD,H.T.	CENTER TOWN.	IND.	396.4	7.0	2267	2163700	34.3	29.40	0.00	49
18	MINNESOTA POWER & LIGHT CO.	AURORA.	AURORA.	MINN	116.1	2.0	1099	436000	45.1	40.00	0.00	53
19	OHIO EDISON CO.	BURGER,R.E.	DILLS BOTTOM.	OHIO	653.6	10.0	3878	13354000	43.3	513.20	8.80	44
20	OHIO EDISON CO.	GORGE.	AKRON.	OHIO	100.6	2.0	1311	1118000	39.5	78.20	0.00	43
21	PENNSYLVANIA POWER & LIGHT CO.	SUNBURY.	SUNBURY.	PA.	409.8	10.0	3970	15915000	39.1	276.00	0.00	49
22	WEST PENN POWER CO.	MILESBURG.	MILESBURG.	PA.	46.0	2.0	573	603000	35.1	57.40	0.00	50
23	WEST PENN POWER CO.	SPRINGDALE.	SPRINGDALE.	PA.	215.4	5.0	1584	1704000	43.6	33.65	1.60	45
24	WEST PENN POWER CO.	MITCHELL.	COURTNEY.	PA.	448.7	4.0	2262	3056000	39.5	329.60	12.50	48
25	DAIRYLAND POWER COOPERATIVE.	ALMA.	ALMA.	WISC	187.8	5.0	1518	244800	57.8	79.50	0.00	47
26	DAIRYLAND POWER COOPERATIVE.	STONEMAN.	CASSVILLE.	WISC	51.8	2.0	706	69900	53.7	15.10	0.00	50

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE I

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	PK1*** PK2	PL#	MP**	ESP***	STACK**	E*
1	GULF POWER CO.	SCHOLZ.	SNEADS.	FLA.	98.0	0.0750	16943	106000	0	58100	11161
2	ELECTRIC ENERGY INC.	JOPPA.	JOPPA.	ILL.	1100.3	0.0375	19051	920000	11784000	756000	138633
3	KENTUCKY UTILITIES CO.	GREEN RIVER.	S.CARROLTON.	KY.	263.6	0.0913	18512	229250	1687360	141110	26544
4	THE POTOMAC EDISON CO.	SMITH,R.PAUL.	WILLIAMSPORT	MD.	110.5	0.0863	13501	180000	1594000	59000	15875
5	CONSUMERS POWER CO.	WHITING.J.R.	ERIE.	MICH	325.0	0.0863	18144	216500	4440000	209000	31401
6	DETROIT PUBLIC LIGHTING COMMISSION.	MISTERSKY.	DETROIT.	MICH	174.0	0.0766	10577	0	211200	23500	21249
7	NEW YORK STATE ELEC.&.GAS CORP.	HICKLING.	EAST CORNING.	N.Y.	86.5	0.0763	15926	108300	0	55300	9529
8	NIAGARA-MOHAWK POWER CORP.	DUNKIRK.	DUNKIRK.	N.Y.	628.0	0.0825	23248	0	18900000	617800	88967
9	DUKE POWER CO.	DAN RIVER.	DRAPER.	N.C.	290.0	0.0775	11942	93000	3693000	57980	27689
10	BLACK HILLS POWER & LIGT CO.	OSAGE.	OSAGE.	WYO.	34.5	0.0780	11171	26000	0	7800	2929
11	TENNESSEE VALLEY AUTHORITY.	JOHNSONVILLE	JOHNSONVILLE.	TENN	1485.2	0.0775	14734	731000	0	360000	130582
12	TENNESSEE VALLEY AUTHORITY.	SHAWNEE.	PADUCAH.	KY.	1750.0	0.0775	13539	377200	8050600	1830000	170650
13	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"A".	STEVENSON.	ALA.	853.0	0.0775	18587	553200	0	192000	66786
14	MONONGAHELA POWER CO.	ALBRIGHT.	ALBRIGHT.	W.VA	278.3	0.0788	15058	424000	673000	202000	29077
15	MONONGAHELA POWER CO.	RIVERSVILLE.	RIVERSVILLE.	W.VA	109.8	0.0788	16122	465000	0	26000	13597
16	MONONGAHELA POWER CO.	WILLOW ISLAND.	ST.MARY'S.	W.VA	215.0	0.0788	20677	120000	407000	156000	27552
17	INDIANAPOLIS POWER & LIGHT CO.	PRITCHARD,H.T.	CENTER TOWN.	IND.	396.4	0.0765	19216	147200	1767000	249500	40130
18	MINNESOTA POWER & LIGHT CO.	AURORA.	AURORA.	MINN	116.1	0.0813	20811	51000	0	365000	17146
19	OHIO EDISON CO.	BURGER,R.E.	DILLS BOTTOM.	OHIO	653.6	0.0850	14030	23000	9254000	4077000	67008
20	OHIO EDISON CO.	GORGE.	AKRON.	OHIO	100.6	0.0850	14585	0	1071000	47000	7588
21	PENNSYLVANIA POWER & LIGHT CO.	SUNBURY.	SUNBURY.	PA.	409.8	0.0750	18499	12000000	3578000	337000	63007
22	WEST PENN POWER CO.	MILESBURG.	MILESBURG.	PA.	46.0	0.0763	18213	0	438000	165000	6367
23	WEST PENN POWER CO.	SPRINGDALE.	SPRINGDALE.	PA.	215.4	0.0763	13053	1604000	0	100000	25240
24	WEST PENN POWER CO.	MITCHELL.	COURTNEY.	PA.	448.7	0.0763	20971	0	2810000	246000	50487
25	DAIRYLAND POWER COOPERATIVE.	ALMA.	ALMA.	WISC	187.8	0.0766	19028	104800	0	140000	21200
26	DAIRYLAND POWER COOPERATIVE.	STONEMAN.	CASSVILLE.	WISC	51.8	0.0766	15325	45500	0	24400	5622

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA
(1973)

VINTAGE II

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	Y1*	Y2**	K1#	L*	F#	F11#	PY#
27	SOUTHERN ELEC GENERATING CO.	GASTON,E.C.	WILSON-VILLE.	ALA.	1060.8	6745	339	5073151	206	64224938	9522	5507
28	COMMONWEALTH EDISON CO.	WILL COUNTY.	LOCKPORT.	ILL.	1268.9	4940	218	12280555	309	51813866	10488	11003
29	ILLINOIS POWER CO.	VERMILLION.	OAKWOOD.	ILL.	182.3	779	41	1804587	67	8571841	10998	9068
30	INDIANA-KENTUCKY ELECTRIC CORP.	CLIFTY CREEK.	MADISON.	IND.	1303.6	9353	457	4692170	342	87348601	9339	4432
31	MISSOURI PUBLIC SERVICE CO.	SIBLEY.	SIBLEY.	MO.	518.5	1799	92	5139757	99	19562265	10877	8022
32	CENTRAL ELEC.POWER COOPERATIVE.	CHAMOIS.	CHAMOIS.	MO.	67.7	245	11	789132	32	2827545	11541	10546
33	NEW YORK STATE ELEC.&.GAS CORP.	GOUDEY.	BINGHAMPTON.	N.Y.	160.8	673	60	1065904	65	7252384	10773	9266
34	NEW YORK STATE ELEC.&.GAS CORP.	MILLIKEN.	LAKE RIDGE.	N.Y.	310.5	1983	136	2375588	65	18892041	9527	6781
35	DUKE POWER CO.	ALLEN,G.G.	BELMONT.	N.C.	1155.0	7747	365	7255749	130	71250998	9197	6289
36	MONTANA-DAKOTA UTILITIES CO.	HESKETT,R.M.	MANDAN.	N.D.	100.0	576	32	1105558	47	7591514	13182	6537
37	OHIO VALLEY ELECTRIC CORP.	KYGER CREEK	CHESHIRE.	OHIO	1086.3	8150	497	4294242	282	76676141	9408	4199
38	PENNSYLVANIA POWER AND LIGHT CO.	BRUNNER ISLAND.	YORK HAVEN.	PA.	1558.7	9534	513	10697460	199	94019377	9862	7035
39	WEST PENN POWER CO.	ARMSTRONG.	REESDALE.	PA.	326.4	2111	173	2969188	58	21594376	10228	6342
40	TENNESSEE VALLEY AUTHORITY.	COLBERT"A".	PRIDE.	ALA.	846.5	4401	289	6024487	225	43393860	9860	6447
41	TENNESSEE VALLEY AUTHORITY.	GALLATIN.	GALLATIN.	TENN	1255.2	6878	486	8676158	284	65406927	9510	5459
42	TENNESSEE VALLEY AUTHORITY.	KINGSTON.	KINGSTON.	TENN	1700.0	9577	828	12492315	521	92893990	9700	6069
43	TENNESSEE VALLEY AUTHORITY.	SEVIER JOHN.	ROGERSVILLE.	TENN	823.3	4474	203	6160232	235	42370674	9470	6228
44	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"B".	STEVENSON.	ALA.	1125.0	4116	264	9452267	332	39762492	9660	8107
45	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC1	CASTLEGATE.	UT.	75.0	412	33	775636	27	4843592	11762	7063
46	UPPER PENINSULA GENERATING CO.	PRESQUE ISLE.	MARQUETTE.	MICH	174.7	1136	39	2006215	58	12822001	11283	10216
47	PUBLIC SERVICE CO OF NEWHAMPSHIRE.	MERRIMACK.	BOW.	N.H.	459.2	2750	72	4111097	74	28150405	10238	7851
48	OHIO EDISON CO.	NILES.	NILES.	OHIO	312.6	1458	103	2398638	84	15604974	10703	6819
49	OHIO EDISON CO.	SAMMIS,W.H.	STRATTON.	OHIO	2455.6	12945	832	25584947	377	121528599	9388	6967
50	OHIO POWER CO.	KAMMER.	CHESAPS.	W.VA	712.5	3794	193	6473360	202	37416428	9862	6256
51	PENNSYLVANIA POWER & LIGHT CO.	HOLTWOOD.	HOLTWOOD.	PA.	75.0	552	62	1141570	40	7227615	13103	8962
52	PENNSYLVANIA POWER & LIGHT CO.	MARTIN'S CREEK.	STROUDSBERG.	PA.	312.5	1748	88	2537237	113	20109545	11503	9495
53	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC2	CASTLEGATE.	UT	113.6	580	33	922358	27	6150234	10613	5960
54	WISCONSIN POWER & LIGHT CO.	DEWEY NELSON.	CASSVILLE.	WISC	227.2	1371	50	2199171	50	13121555	9568	6346

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE II

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	EMNO**	TP*	E2#	PFF*	T*	S**	YR*
27	SOUTHERN ELEC GENERATING CO.	GASTON.E.C.	WILSON-VILLE.	ALA.	1060.8	4.0	3429	5473210	44.1	445.60	5.60	61
28	COMMONWEALTH EDISON CO.	WILL COUNTY.	LOCKPORT.	ILL.	1268.9	4.0	7725	13514000	64.0	1511.00	0.00	55
29	ILLINOIS POWER CO.	VERMILLION.	OAKWOOD.	ILL.	182.3	2.0	1300	1720000	44.7	39.50	0.20	55
30	INDIANA-KENTUCKY ELECTRIC CORP.	CLIFTY CREEK.	MADISON.	IND.	1303.6	6.0	5733	6276000	35.2	859.00	23.00	55
31	MISSOURI PUBLIC SERVICE CO.	SIBLEY.	SIBLEY.	MO.	518.5	3.0	2987	4691000	30.2	283.20	19.35	61
32	CENTRAL ELEC.POWER COOPERATIVE.	CHAMOIS.	CHAMOIS.	MO.	67.7	1.0	418	59400	48.4	21.50	0.00	54
33	NEW YORK STATE ELEC.&.GAS CORP.	GOUDEY.	BINGHAMPTON.	N.Y.	160.8	6.0	1312	4797590	48.2	106.10	0.00	61
34	NEW YORK STATE ELEC.&.GAS CORP.	MILLIKEN.	LAKE RIDGE.	N.Y.	310.5	2.0	1313	6789680	48.5	768.20	0.00	55
35	DUKE POWER CO.	ALLEN,G.G.	BELMONT.	N.C.	1155.0	5.0	3853	24037600	50.2	169.50	2.80	57
36	MONTANA-DAKOTA UTILITIES CO.	HESKETT,R.M.	MANDAN.	N.D.	100.0	2.0	709	188500	25.4	95.10	0.00	54
37	OHIO VALLEY ELECTRIC CORP.	KYGER CREEK	CHESHIRE.	OHIO	1086.3	5.0	5296	4886000	31.8	807.00	84.00	55
38	PENNSYLVANIA POWER AND LIGHT CO.	BRUNNER ISLAND.	YORK HAVEN.	PA.	1558.7	3.0	6658	4864000	52.4	652.00	0.00	61
39	WEST PENN POWER CO.	ARMSTRONG.	REESDALE.	PA.	326.4	2.0	1859	1522000	39.0	185.00	5.70	58
40	TENNESSEE VALLEY AUTHORITY.	COLBERT"A".	PRIDE.	ALA.	846.5	7.0	4295	9141100	39.9	393.00	5.00	55
41	TENNESSEE VALLEY AUTHORITY.	GALLATIN.	GALLATIN.	TENN	1255.2	2.0	4526	6468000	36.4	424.00	20.60	56
42	TENNESSEE VALLEY AUTHORITY.	KINGSTON.	KINGSTON.	TENN	1700.0	9.0	7686	3507000	40.5	547.00	51.00	54
43	TENNESSEE VALLEY AUTHORITY.	SEVIER JOHN.	ROGERSVILLE.	TENN	823.3	6.0	3614	7193200	41.2	552.00	0.00	55
44	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"B".	STEVENSON.	ALA.	1125.0	2.0	8459	2421000	38.2	619.00	0.00	61
45	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC1	CASTLEGATE.	UT.	75.0	2.0	686	116770	29.5	83.00	0.13	54
46	UPPER PENINSULA GENERATING CO.	PRESQUE ISLE.	MARQUETTE.	MICH	174.7	8.0	971	4715000	64.1	60.30	0.00	55
47	PUBLIC SERVICE CO OF NEWHAMPSHIRE.	MERRIMACK.	BOW.	N.H.	459.2	2.0	3018	1159000	51.0	168.00	70.40	60
48	OHIO EDISON CO.	NILES.	NILES.	OHIO	312.6	2.0	1788	276000	36.6	221.30	17.60	54
49	OHIO EDISON CO.	SAMMIS,W.H.	STRATTON.	OHIO	2455.6	6.0	15717	11107000	39.3	1494.80	12.50	59
50	OHIO POWER CO.	KAMMER.	CHESAPS.	W.VA	712.5	3.0	4348	1328300	34.1	299.73	0.00	59
51	PENNSYLVANIA POWER & LIGHT CO.	HOLTWOOD.	HOLTWOOD.	PA.	75.0	4.0	1277	1358000	33.6	45.00	0.00	54
52	PENNSYLVANIA POWER & LIGHT CO.	MARTIN'S CREEK.	STROUDSBERG.	PA.	312.5	2.0	2436	2432000	56.9	97.80	1.00	54
53	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC2	CASTLEGATE.	UT	113.6	2.0	704	176880	29.4	83.00	0.13	57
54	WISCONSIN POWER & LIGHT CO.	DEWEY NELSON.	CASSVILLE.	WISC	227.2	0.0	790	185000	43.4	58.70	0.00	59

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE II

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	PK1*** PK2	PL#	MP**	ESP***	STACK**	E*
27	SOUTHERN ELEC GENERATING CO.	GASTON,E.C.	WILSON-VILLE.	ALA.	1060.8	0.0525	14815	0	4831210	642000	95842
28	COMMONWEALTH EDISON CO.	WILL COUNTY.	LOCKPORT.	ILL.	1268.9	0.0763	22250	0	12454000	1060000	165606
29	ILLINOIS POWER CO.	VERMILLION.	OAKWOOD.	ILL.	182.3	0.0763	17269	65000	1420000	235000	23568
30	INDIANA-KENTUCKY ELECTRIC CORP.	CLIFTY CREEK.	MADISON.	IND.	1303.6	0.0375	14919	0	3390000	2686000	117036
31	MISSOURI PUBLIC SERVICE CO.	SIBLEY.	SIBLEY.	MO.	518.5	0.0788	26853	0	3507000	1184000	66154
32	CENTRAL ELEC.POWER COOPERATIVE.	CHAMOIS.	CHAMOIS.	MO.	67.7	0.0756	11626	15600	0	43800	9792
33	NEW YORK STATE ELEC.&.GAS CORP.	GOUDEY.	BINGHAMPTON.	N.Y.	160.8	0.0763	17964	0	4717300	80290	17037
34	NEW YORK STATE ELEC.&.GAS CORP.	MILLIKEN.	LAKE RIDGE.	N.Y.	310.5	0.0763	17978	0	5700000	1089680	37159
35	DUKE POWER CO.	ALLEN,G.G.	BELMONT.	N.C.	1155.0	0.0775	26378	13955000	9488000	594600	112428
36	MONTANA-DAKOTA UTILITIES CO.	HESKETT,R.M.	MANDAN.	N.D.	100.0	0.0763	13426	95600	0	92900	13602
37	OHIO VALLEY ELECTRIC CORP.	KYGER CREEK	CHESHIRE.	OHIO	1086.3	0.0375	16714	0	2675000	2211000	105985
38	PENNSYLVANIA POWER AND LIGHT CO.	BRUNNER ISLAND.	YORK HAVEN.	PA.	1558.7	0.0750	29777	0	3578000	1286000	138688
39	WEST PENN POWER CO.	ARMSTRONG.	REESDALE.	PA.	326.4	0.0763	28526	0	1338000	164000	38039
40	TENNESSEE VALLEY AUTHORITY.	COLBERT"A".	PRIDE.	ALA.	846.5	0.0775	16989	239700	8377400	524000	81331
41	TENNESSEE VALLEY AUTHORITY.	GALLATIN.	GALLATIN.	TENN	1255.2	0.0775	14184	229000	5524000	715000	112567
42	TENNESSEE VALLEY AUTHORITY.	KINGSTON.	KINGSTON.	TENN	1700.0	0.0775	13130	0	2409000	1098000	154493
43	TENNESSEE VALLEY AUTHORITY.	SEVIER JOHN.	ROGERSVILLE.	TENN	823.3	0.0775	13687	282400	6538800	372000	82334
44	TENNESSEE VALLEY AUTHORITY.	WIDOWS CREEK"B".	STEVENSON.	ALA.	1125.0	0.0775	22676	0	1737000	684000	113258
45	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC1	CASTLEGATE.	UT.	75.0	0.0750	22613	0	69070	47700	9574
46	UPPER PENINSULA GENERATING CO.	PRESQUE ISLE.	MARQUETTE.	MICH	174.7	0.0863	14900	119000	4481000	115000	26614
47	PUBLIC SERVICE CO OF NEWHAMPSHIRE.	MERRIMACK.	BOW.	N.H.	459.2	0.0763	36298	0	766000	393000	50662
48	OHIO EDISON CO.	NILES.	NILES.	OHIO	312.6	0.0850	18944	172000	0	104000	26445
49	OHIO EDISON CO.	SAMMIS,W.H.	STRATTON.	OHIO	2455.6	0.0850	37104	0	3498000	7609000	293685
50	OHIO POWER CO.	KAMMER.	CRESAPS.	W.VA	712.5	0.0888	19157	185300	0	1143000	69250
51	PENNSYLVANIA POWER & LIGHT CO.	HOLTWOOD.	HOLTWOOD.	PA.	75.0	0.0750	28413	0	1251000	107000	14772
52	PENNSYLVANIA POWER & LIGHT CO.	MARTIN'S CREEK.	STROUDSBERG.	PA.	312.5	0.0750	19186	0	2200000	232000	32831
53	UTAH POWER & LIGHT CO.	CARBON COUNTY SEC2	CASTLEGATE.	UT	113.6	0.0750	23206	0	104630	72250	11564
54	WISCONSIN POWER & LIGHT CO.	DEWEY NELSON.	CASSVILLE.	WISC	227.2	0.0888	14062	0	0	185000	24058

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE III

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY	Y1*	Y2**	K1	L*	F#	F11#	PY#
55	ALABAMA POWER CO.	GREENE COUNTY.	DEMOPOLIS.	ALA.	586.5	3121	171	3891228	129	30388003	9736	5529
56	TAMPA ELECTRIC CO.	BIG BEND.	TAMPA.	FLA.	891.5	3702	360	9522665	114	37822949	10218	8256
57	COMMONWEALTH EDISON CO.	KINKAID.	KINKAID.	ILL.	1319.4	4903	400	9937747	190	51590060	10523	7797
58	ALCOA GENERATING CORP.	WARICK UNITS 1,2,3	NEWBURG.	IND.	432.0	3037	219	4080884	115	33386002	10992	5013
59	INDIANAPOLIS POWER & LIGHT CO.	PETERSBURG.	PETERSBURG.	IND.	732.7	3910	165	5888638	97	37903572	9695	5164
60	LOUISVILLE GAS & ELECTRIC CO.	MILLCREEK.	LOUISVILLE.	KY.	355.5	1366	83	3345826	83	13437504	9840	7416
61	NORTHERN STATES POWER CO.MINN.	KING,ALLEN.S.	OAK-PARK HEIGH	MINN	598.4	2993	204	5169602	94	28657018	9575	7355
62	BASIN ELECTRIC POWER COOP.	LELAND OLDS.	STANTON.	N.D.	240.0	1435	88	1766906	58	15334378	10683	3941
63	WEST PENN POWER CO.	HATFIELD'S FERRY	MASON TOWN.	PA.	1728.0	9469	759	16684205	146	69920473	9496	5402
64	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	GRAINGER.	CONWAY.	S.C.	163.2	1061	61	1354396	50	10444176	9840	6687
65	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	JEFFRIES UNITS 3&4	MONCKS CORNER.	S.C.	345.6	2036	103	2818149	65	19089214	9374	6460
66	TENNESSEE VALLEY AUTHORITY.	BULL RUN	CLINTON.	TENN	950.0	5892	290	8802890	208	53206566	9030	5003
67	TENNESSEE VALLEY AUTHORITY.	COLBERT"B"	PRIDE.	ALA.	550.0	2250	99	4619995	147	22118483	9830	7151
68	TENNESSEE VALLEY AUTHORITY.	CUMBERLAND.	CUMBERLAND.	TENN	1300.0	1394	632	12627623	273	13742868	9860	15146
69	TENNESSEE VALLEY AUTHORITY.	PARADISE"A".	DRAKESBORO.	KY.	1408.0	8245	690	13130360	334	78492400	9520	4608
70	TENNESSEE VALLEY AUTHORITY.	PARADISE"B".	DRAKESBORO.	KY.	1150.2	6277	526	10420695	272	59572526	9490	4478
71	MONONGAHELA POWER CO.	HARRISON.	SHINSTON.	W.VA	1368.0	2303	132	17912200	91	21976014	9544	12233
72	COLORADO-UTE ELECTRIC ASSOC.INC.	HAYDEN.	HAYDEN.	COL.	163.2	1376	62	1613567	50	13703204	9958	3723
73	ILLINOIS POWER CO.	BALDWIN.	BALDWIN.	ILL.	1257.6	6575	477	12548631	144	65542590	9968	4924
74	INDIANA STATEWIDE RURAL ELEC COOP.	RATTS,FRANK.E.	PIKE COUNTY.	IND.	233.2	1502	92	2410656	41	14979433	9971	5234
75	PENNSYLVANIA POWER & LIGHT CO.	MONTOUR.	COLUMBIA CO.	PA.	1641.7	7532	406	16719020	152	75333064	10002	7787
76	UTAH POWER & LIGHT CO.	NAUGHTON NO.1	KEMMERER.	WYO.	163.2	1188	48	1497977	23	12139813	10223	4406
77	UTAH POWER & LIGHT CO.	NAUGHTON NO.2	KEMMERER.	WYO.	217.6	1420	58	1710199	23	14457636	10180	4254
78	MONONGAHELA POWER CO.	FORT MARTIN.	MORGAN TOWN.	W.VA	1152.0	7149	450	10107811	159	66532951	9307	5069
79	DAIRYLAND POWER COOPERATIVE.	NEW GENOA.	GENOA.	WISC	345.6	1631	180	3389790	65	15021931	9206	8454
80	WISCONSIN POWER & LIGHT CO.	EDGEWATER UNIT 4.	SHEBOYGAN.	WISC	351.0	2211	116	3243841	61	21608359	9774	6800

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE III

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	EMNO**	TP*	E2#	PFF*	T*	S**	YR*
55	ALABAMA POWER CO.	GREENE COUNTY.	DEMOPOLIS.	ALA.	586.5	2.0	2799	1367000	34.4	126.70	0.00	65
56	TAMPA ELECTRIC CO.	BIG BEND.	TAMPA.	FLA.	891.5	2.0	2406	1152000	49.0	307.10	306.10	72
57	COMMONWEALTH EDISON CO.	KINKAID.	KINKAID.	ILL.	1319.4	4.0	9676	5292000	34.9	1809.00	0.00	67
58	ALCOA GENERATING CORP.	WARICK UNITS 1,2,3	NEWBURG.	IND.	432.0	4.0	2676	2526000	24.7	210.00	0.00	64
59	INDIANAPOLIS POWER & LIGHT CO.	PETERSBURG.	PETERSBURG.	IND.	732.7	2.0	3318	3279000	28.3	201.90	0.00	68
60	LOUISVILLE GAS & ELECTRIC CO.	MILLCREEK.	LOUISVILLE.	KY.	355.5	1.0	1737	3739000	35.3	150.40	0.00	72
61	NORTHERN STATES POWER CO.MINN.	KING,ALLEN.S.	OAK-PARK HEIGH	MINN	598.4	1.0	3956	3005000	44.1	220.50	2.70	68
62	BASIN ELECTRIC POWER COOP.	LELAND OLDS.	STANTON.	N.D.	240.0	1.0	1326	1121220	16.1	47.90	8.70	66
63	WEST PENN POWER CO.	HATFIELD'S FERRY	MASUN TOWN.	PA.	1728.0	3.0	5432	6979000	31.6	1115.60	1.60	69
64	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	GRAINGER.	CONWAY.	S.C.	163.2	2.0	807	761000	48.7	24.00	0.00	65
65	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	JEFFRIES UNITS 3&4	MONCKS CORNER.	S.C.	345.6	4.0	847	1038000	49.3	38.90	0.00	70
66	TENNESSEE VALLEY AUTHORITY.	BULL RUN	CLINTON.	TENN	950.0	1.0	3230	2925000	32.3	188.00	0.00	67
67	TENNESSEE VALLEY AUTHORITY.	COLBERT"B"	PRIDE.	ALA.	550.0	1.0	2548	1171000	39.9	159.00	0.00	65
68	TENNESSEE VALLEY AUTHORITY.	CUMBERLAND.	CUMBERLAND.	TENN	1300.0	2.0	1704	15567500	40.2	496.00	0.00	73
69	TENNESSEE VALLEY AUTHORITY.	PARADISE"A".	DRAKESBORO.	KY.	1409.0	2.0	8045	4218300	20.9	1041.24	10.21	63
70	TENNESSEE VALLEY AUTHORITY.	PARADISE"B".	DRAKESBORO.	KY.	1150.2	1.0	5078	3446000	20.6	792.76	7.97	70
71	MONONGAHELA POWER CO.	HARRISON.	SHINSTON.	W.VA	1368.0	2.0	2328	11725000	31.9	41.80	1.50	72
72	COLORADO-UTE ELECTRIC ASSOC.INC.	HAYDEN.	HAYDEN.	COL.	163.2	1.0	855	794000	18.9	32.70	0.00	65
73	ILLINOIS POWER CO.	BALDWIN.	BALDWIN.	ILL.	1257.6	2.0	2752	7205000	25.2	155.50	1.00	70
74	INDIANA STATEWIDE RURAL ELEC COOP.	RATTS,FRANK.E.	PIKE COUNTY.	IND.	233.2	2.0	661	464000	31.7	25.00	0.00	69
75	PENNSYLVANIA POWER & LIGHT CO.	MONTOUR.	COLUMBIA CO.	PA.	1641.7	2.0	5600	7210000	47.5	253.00	0.00	72
76	UTAH POWER & LIGHT CO.	NAUGHTON NO.1	KEMMERER.	WYO.	163.2	0.5	560	863060	25.6	38.35	0.00	63
77	UTAH POWER & LIGHT CO.	NAUGHTON NO.2	KEMMERER.	WYO.	217.6	0.5	570	1151100	25.4	45.85	0.00	68
78	MONONGAHELA POWER CO.	FORT MARTIN.	MORGAN TOWN.	W.VA	1152.0	2.0	4025	5652000	32.5	234.00	2.00	67
79	DAIRYLAND POWER COOPERATIVE.	NEW GENOA.	GENOA.	WISC	345.6	1.0	2059	1416000	54.7	236.80	15.00	69
80	WISCONSIN POWER & LIGHT CO.	EDGEWATER UNIT 4.	SHEBOYGAN.	WISC	351.0	3.0	1225	1580000	48.1	261.40	0.00	69

TABLE 15

COAL-FIRED ELECTRIC PLANTS CONSTRUCTION, PRODUCTION EXPENSES, AND AIR QUALITY CONTROL DATA (1973)

VINTAGE III

NO	UTILITY CO.	PLANT	CITY	STATE	CAPACITY*	PK1*** PK2	PL#	MP**	ESP***	STACK**	E*
55	ALABAMA POWER CO.	GREENE COUNTY.	DEMOPOLIS.	ALA.	586.5	0.0825	19311	0	1071000	296000	44973
56	TAMPA ELECTRIC CO.	BIG BEND.	TAMPA.	FLA.	891.5	0.0850	18784	0	540000	612000	110071
57	COMMONWEALTH EDISON CO.	KINKAID.	KINKAID.	ILL.	1319.4	0.0763	45324	0	4342000	950000	124274
58	ALCOA GENERATING CORP.	WARICK UNITS 1,2,3	NEWBURG.	IND.	432.0	0.0766	20710	259000	723000	1544000	52260
59	INDIANAPOLIS POWER & LIGHT CO.	PETERSBURG.	PETERSBURG.	IND.	732.7	0.0765	30444	0	2507000	772000	75774
60	LOUISVILLE GAS & ELECTRIC CO.	MILLCREEK.	LOUISVILLE.	KY.	355.5	0.0750	18626	0	1486000	2253000	46023
61	NORTHERN STATES POWER CO.MINN.	KING,ALLEN.S.	OAK-PARK HEIGH	MINN	598.4	0.0750	37456	0	1370000	1635000	66453
62	BASIN ELECTRIC POWER COOP.	LELAND OLDS.	STANTON.	N.D.	240.0	0.0766	20347	145000	0	976220	22340
63	WEST PENN POWER CO.	HATFIELD'S FERRY	MASON TOWN.	PA.	1728.0	0.0763	33113	0	4776000	2203000	219559
64	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	GRAINGER.	CONWAY.	S.C.	163.2	0.0766	14365	0	423000	338000	17318
65	SOUTH CAROLINA PUBLIC SERVICE AUTHO.	JEFFRIES UNITS 3&4	MONCKS CORNER.	S.C.	345.6	0.0766	11597	52000	354000	632000	36568
66	TENNESSEE VALLEY AUTHORITY.	BULL RUN	CLINTON.	TENN	950.0	0.0775	13821	0	1701000	1224000	112193
67	TENNESSEE VALLEY AUTHORITY.	COLBERT"B"	PRIDE.	ALA.	550.0	0.0775	15427	0	744000	427000	57393
68	TENNESSEE VALLEY AUTHORITY.	CUMBERLAND.	CUMBERLAND.	TENN	1300.0	0.0775	5555	0	7775000	7792500	176790
69	TENNESSEE VALLEY AUTHORITY.	PARADISE"A".	DRAKESBORO.	KY.	1408.0	0.0775	21437	0	3688900	529400	163687
70	TENNESSEE VALLEY AUTHORITY.	PARADISE"B".	DRAKESBORO.	KY.	1150.2	0.0775	16615	0	3013500	432500	131813
71	MONONGAHELA POWER CO.	HARRISON.	SHINSTON.	W.VA	1368.0	0.0788	22768	0	4725000	7000000	235986
72	COLORADO-UTE ELECTRIC ASSOC.INC.	HAYDEN.	HAYDEN.	COL.	163.2	0.0766	15219	0	579000	215000	20678
73	ILLINOIS POWER CO.	BALDWIN.	BALDWIN.	ILL.	1257.6	0.0763	17009	0	4700000	2505000	168030
74	INDIANA STATEWIDE RURAL ELEC COOP.	RATTS,FRANK.E.	PIKE COUNTY.	IND.	233.2	0.0766	14349	0	146000	318000	31024
75	PENNSYLVANIA POWER & LIGHT CO.	MONTOUR.	COLUMBIA CO.	PA.	1641.7	0.0750	32789	0	4725000	2485000	222268
76	UTAH POWER & LIGHT CO.	NAUGHTON NO.1	KEMMERER.	WYO.	163.2	0.0750	21670	135460	349000	378600	20071
77	UTAH POWER & LIGHT CO.	NAUGHTON NO.2	KEMMERER.	WYO.	217.6	0.0750	22057	180600	465700	504800	23165
78	MONONGAHELA POWER CO.	FORT MARTIN.	MORGAN TOWN.	W.VA	1152.0	0.0788	22530	0	4121000	1531000	128707
79	DAIRYLAND POWER COOPERATIVE.	NEW GENOA.	GENOA.	WISC	345.6	0.0766	21559	0	811000	605000	43030
80	WISCONSIN POWER & LIGHT CO.	EDGEWATER UNIT 4.	SHEBOYGAN.	WISC	351.0	0.0888	17873	0	1106000	474000	36936

SOURCES: *Federal Power Commission, 1976b.
**Federal Power Commission, 1976a.
***Hanson, 1974.
#See Appendix B.

Appendix D

Definitions

BTU:	The quantity of heat required to raise the temperature of one pound of water by one degree Fahrenheit is called the British Thermal Unit (BTU).
Megawatt (MW):	1,000 kilowatts.
KW-hr:	Kilowatt hour--the amount of energy equal to 1 kilowatt in one hour. It is equivalent to 3,412 BTU.
Net Generation:	Gross generation less kilowatt hours consumed out of gross generation for station use.
Vintage:	Vintage year of a machine refers to the initial years of commercial operation of the plant.

Appendix E

Derivation of Constraints for the Nonlinear Separability Conditions

In order to arrive at the required constraints for equality of AES between α_{ij} and α_{Kj} for $i \neq K$, the derivation for the following example is carried out:[49]

Assume:

$$\alpha_{LF} = \alpha_{K_2F} \tag{42}$$

which is equivalent to:

$$N_{K_2}\beta_{LF} = N_L\beta_{K_2F} \tag{43}$$

or

$$N_{K_2}\beta_{LF} - N_L\beta_{K_2F} = 0 \tag{44}$$

This was shown in the separability test section of Chapter III. Using the share equations, substituting for N_L and N_{K_2}:

$$\begin{aligned} &\beta_{LF}(\alpha_{K_2} + \beta_{K_2K_1}\ln P_{K_1} + \beta_{K_2L}\ln P_L + \beta_{K_2F}\ln P_F \\ &+ \delta_{K_2Y_1}\ln Y_1 + \delta_{K_2Y_2}\ln Y_2) - \beta_{K_2F}(\alpha_L + \beta_{LK_1}\ln P_{K_1} \\ &+ \beta_{LL}\ln P_L + \beta_{LF}\ln P_F + \delta_{LY_1}\ln Y_1 + \delta_{LY_2}\ln Y_2) = 0 \end{aligned} \tag{45}$$

For this relationship to hold as a necessary condition, the following equations should be satisfied:

$$\frac{\alpha_{K_2}}{\alpha_L} = \frac{\beta_{K_2F}}{\beta_{LF}} \qquad \frac{\beta_{K_2F}}{\beta_{LF}} = \frac{\beta_{K_2L}}{\beta_{LL}} \qquad \frac{\beta_{K_2F}}{\beta_{LF}} = \frac{\delta_{K_2Y_2}}{\delta_{LY_2}}$$

$$\frac{\beta_{K_2F}}{\beta_{LF}} = \frac{\beta_{K_2K_1}}{\beta_{LK_1}} \qquad \frac{\beta_{K_2F}}{\beta_{LF}} = \frac{\delta_{K_2Y_1}}{\delta_{LY_1}} \qquad (46)-(50)$$

---

[49]Similar derivation is applicable to other conditions where equality of substitution elasticities between a pair of input and any other factors is required.

For these last five equalities to hold, the following parametric restrictions are imposed on the coefficients of the cost function and share equations:

$$\alpha_{K_2} = \alpha_L \frac{\beta_{K_2F}}{\beta_{LF}} , \quad \beta_{K_2K_1} = \frac{\beta_{K_2F}}{\beta_{LF}} \beta_{LK_1} \tag{51}$$

$$\beta_{K_2L} = \frac{\beta_{K_2F}}{\beta_{LF}} \beta_{LL} , \quad \alpha_L = \alpha_{K_2} \frac{\beta_{LF}}{\beta_{K_2F}} \tag{52}$$

$$\beta_{LK_1} = \beta_{K_2K_1} \frac{\beta_{LF}}{\beta_{K_2F}} , \quad \beta_{LL} = \beta_{K_2L} \frac{\beta_{LF}}{\beta_{K_2F}} \tag{53}$$

$$\delta_{K_{21}} = \frac{\beta_{K_2F}}{\beta_{LF}} \delta_{L_1} , \quad \delta_{K_{22}} = \frac{\beta_{K_2F}}{\beta_{LF}} \delta_{L_2} \tag{54}$$

$$\delta_{LY_1} = \delta_{K_2Y_1} \frac{\beta_{LF}}{\beta_{K_2F}} , \quad \delta_{LY_2} = \delta_{K_2Y_2} \frac{\beta_{LF}}{\beta_{K_2F}} \tag{55}$$

Appendix F

Parameter Estimates of Share Equations and the Cost Function in the Exact and the Approximate Models

TABLE 16

PARAMETER ESTIMATES OF THE SHARE EQUATIONS UNDER EXACT MODEL SPECIFICATION (ASYMPTOTIC STANDARD ERRORS IN PARENTHESES)

Vintage I

Parameters	Model		
	A-I	B-I	C-I
α_{K1}	.21004 (.16351)	.20913 (.16021)	.21005 (.16351)
α_{L}	.17103 (.13401)	.17103 (.13401)	.17103 (.13401)
α_{F}	.57620 (.22247)	.60183 (.23207)	.59834 (.22936)
α_{K2}	.01803 (.01148)	.01801 (.01143)	.02058 (.01258)
β_{K1K1}	.12461 (.06572)	---	.09831 (.04965)
β_{K1L}	.06310 (.06439)	---	.00513 (.00517)
β_{K1F}	-.07103 (.06416)	---	-.10344 (.09339)
δ_{K1Y1}	-.03103 (.02795)	---	-.04013 (.03623)
δ_{K1Y2}	.02117 (.02406)	---	.04011 (.04105)
β_{LK1}	-.04210 (.04305)	---	---
β_{LL}	.00153 (.02887)	---	.00155 (.02888)
β_{LF}	-.05032 (.02595)	---	-.00668 (.00267)
δ_{LY1}	-.06115 (.01253)	---	-.05009 (.01002)
δ_{LY2}	.03114 (.01422)	---	.05008 (.02385)
β_{FK1}	-.12603 (.12795)	---	---
β_{FL}	-.07003 (.07167)	---	---
β_{FF}	-.05963 (.03284)	---	.11012 (.05973)
δ_{FY1}	.10006 (.03156)	---	.10006 (.03156)
δ_{FY2}	-.06091 (.06038)	---	-.10005 (.10013)
β_{K2K1}	.03002 (.02981)	---	.09830 (.09572)
β_{K2L}	.00043 (.00089)	---	---
β_{K2F}	.00076 (.00073)	---	---
δ_{K2Y1}	-.00024 (.00025)	---	-.00023 (.00025)
δ_{K2Y2}	.00063 (.00065)	---	.00023 (.00037)
log. det. $\hat{\Sigma}$	-2.59280	3.20124	2.78993

TABLE 16--Continued

Param-eters	Model D-I	E-I	F-I
α_{K1}	.31179 (.50608)	.31179 (.50608)	.16501 (.20314)
α_{L}	.11962 (.12117)	.11962 (.12117)	.18112 (.15503)
α_{F}	.53137 (.60148)	.53937 (.60148)	.57998 (.22259)
α_{K2}	.01449 (.36429) .97724	.01449 (.36429)	.16501 (.28107)
β_{K1K1}	-.07610 (.03756)	-.05148 (.02506)	.10112 (.04815)
β_{K1L}	-.03769 (.04932)	-.03787 (.04943)	.03102 (.03215)
β_{K1F}	-.09179 (.04546)	-.07382 (.03691)	-.09138 (.07833)
δ_{K1Y1}	-.09938 (.04969)	-.00155 (.00077)	-.03181 (.02652)
δ_{K1Y2}	.09998 (.03333)	.09038 (.03013)	.00318 (.00374)
β_{LK1}	---	---	---
β_{LL}	.06954 (.03148)	.06955 (.03148)	.00153 (.02887)
β_{LF}	-.07360 (.01746)	-.02832 (.00944)	-.05031 (.02594)
δ_{LY1}	-.00403 (.00201)	-.00403 (.00201)	-.06113 (.01250)
δ_{LY2}	.00204 (.00108)	.03467 (.00693)	.03114 (.01422)
β_{FK1}	---	---	---
β_{FL}	---	---	---
β_{FF}	.13158 (.03618)	.13158 (.03618)	-.05963 (.03284)
δ_{FY1}	.17072 (.04950)	.17072 (.04950)	.10006 (.03156)
δ_{FY2}	-.15002 (.03447)	-.15002 (.03447)	-.06088 (.06038)
β_{K2K1}	-.03510 (.04038)	-.03510 (.04038)	.03002 (.02981)
β_{K2L}	---	---	---
β_{K2F}	---	---	---
δ_{K2Y1}	-.00049 (.00010)	-.02028 (.00500)	-.03181 (.02771)
δ_{K2Y2}	.00025 (.00006)	.01641 (.00357)	.00318 (.00314)
log. det. $\hat{\Sigma}$	-2.50753	-2.50502	4.41138

TABLE 16--Continued

Parameters	Model G-I	Model H-I	Model I-I	Model J-I
α_{K1}	.21004 (.16351)	.21004 (.16351)	.21004 (.16351)	.21004 (.16351)
α_{L}	.17103 (.13401)	.17103 (.13401)	.17103 (.13401)	.17103 (.13401)
α_{F}	.57620 (.22247)	.57620 (.22247)	.57620 (.22247)	.57620 (.22247)
α_{K2}	.01803 (.01148)	.01803 (.01148)	.01803 (.01148)	.01803 (.01148)
β_{K1K1}	.12461 (.06572)	.09312 (.04656)	.12461 (.06572)	.09312 (.04656)
β_{K1L}	.06310 (.06439)	.00918 (.00923)	.06310 (.06439)	.00918 (.00923)
β_{K1F}	-.07103 (.06416)	---	---	-.07003 (.06302)
δ_{K1Y1}	-.03103 (.02795)	-.03120 (.02836)	-.03103 (.02795)	---
δ_{K1Y2}	.02117 (.02406)	.02119 (.02405)	.02117 (.02406)	---
β_{LK1}	---	---	---	---
β_{LL}	.00155 (.02888)	.00153 (.02887)	.00153 (.02887)	.00153 (.02887)
β_{LF}	---	-.05031 (.02594)	-.05029 (.02594)	-.05031 (.02594)
δ_{LY1}	-.05009 (.01002)	-.06115 (.01253)	-.06115 (.01253)	---
δ_{LY2}	.04385 (.02088)	.03105 (.01413)	.03105 (.01413)	---
β_{FK1}	---	---	---	---
β_{FL}	---	---	---	---
β_{FF}	-.05963 (.03284)	-.05963 (.03884)	-.05963 (.03284)	-.05963 (.03284)
δ_{FY1}	.10006 (.03156)	.10006 (.03156)	.10006 (.03156)	---
δ_{FY2}	-.06091 (.06038)	-.06091 (.06038)	-.06091 (.06038)	---
β_{K2K1}	.03001 (.02981)	.03001 (.02981)	.02775 (.02677)	.03001 (.02981)
β_{K2L}	---	---	---	---
β_{K2F}	---	---	---	---
δ_{K2Y1}	-.00024 (.00025)	-.00024 (.00025)	-.00038 (.00043)	---
δ_{K2Y2}	.00061 (.00065)	.00061 (.00065)	.00057 (.00059)	---
log. det. $\hat{\Sigma}$	4.28007	.39273	4.31275	3.51054

TABLE 17

PARAMETER ESTIMATES OF THE SHARE EQUATIONS UNDER EXACT MODEL SPECIFICATION (ASYMPTOTIC STANDARD ERRORS IN PARENTHESES)

Vintage II

Param-eters	Model A-I	Model B-I	Model C-I
α_{K1}	.22081 (.11040)	.22081 (.11001)	.22002 (.11641)
α_{L}	.13872 (.14981)	.13872 (.15095)	.13774 (.14972)
α_{F}	.60677 (.40451)	.62333 (.42242)	.62612 (.42021)
α_{K2}	.01612 (.01135)	.01714 (.01182)	.01612 (.01135)
β_{K1K1}	.18791 (.03417)	---	.08312 (.01511)
β_{K1L}	.00152 (.00253)	---	.00053 (.00795)
β_{K1F}	-.16234 (.14612)	---	-.08365 (.07529)
δ_{K1Y1}	.02920 (.02631)	---	.02942 (.02648)
δ_{K1Y2}	-.03670 (.02531)	---	-.03618 (.03001)
β_{LK1}	.00673 (.02738)	---	---
β_{LL}	.04432 (.01766)	---	.04138 (.01565)
β_{LF}	-.07281 (.02591)	---	-.04191 (.01450)
δ_{LY1}	-.05481 (.01884)	---	-.05149 (.01776)
δ_{LY2}	.03801 (.02001)	---	.05149 (.02575)
β_{FK1}	.18041 (.05551)	---	---
β_{FL}	-.05219 (.03954)	---	---
β_{FF}	.21150 (.05060)	---	-.12556 (.02283)
δ_{FY1}	.05244 (.04724)	---	.05113 (.03933)
δ_{FY2}	-.02303 (.03495)	---	-.05113 (.05812)
β_{K2K1}	.00048 (.00053)	---	.08311 (.09128)
β_{K2L}	.00042 (.00052)	---	---
β_{K2F}	.00324 (.00113)	---	---
δ_{K2Y1}	-.01913 (.00911)	---	-.01912
δ_{K2Y2}	.01753 (.00928)	---	.01912 (.00999)
log. det. $\hat{\Sigma}$	-.98165	2.33185	1.16517

TABLE 17 --Continued

Parameters	Model D-I	Model E-I	Model F-I
α_{K1}	.22080 (.11040)	.22081 (.11040)	.16432 (.20218)
α_{L}	.13872 (.14981)	.13872 (.14981)	.13872 (.14981)
α_{F}	.60593 (.40321)	.60543 (.40321)	.60593 (.40321)
α_{K2}	.01612 (.01135)	.01612 (.01135)	.16432 (.29104)
β_{K1K1}	.18791 (.03417)	.18783 (.03408)	.18783 (.03408)
β_{K1L}	.00151 (.00252)	.00151 (.00252)	-.09142 (.07138)
β_{K1F}	-.00846 (.08273)	-.11035 (.09131)	-.09142 (.07138)
δ_{K1Y1}	.02920 (.02631)	.02114 (.01953)	-.00603 (.00419)
δ_{K1Y2}	-.03670 (.02531)	-.03126 (.02171)	.00589 (.02315)
β_{LK1}	---	---	---
β_{LL}	.04431 (.01765)	.04431 (.01765)	.04430 (.01764)
β_{LF}	-.07884 (.02592)	-.06933 (.02407)	-.07214 (.02589)
δ_{LY1}	-.05771 (.01862)	.01328 (.00272)	-.05479 (.01880)
δ_{LY2}	.03991 (.02112)	-.01464 (.01034)	.03801 (.02001)
β_{FK1}	---	---	---
β_{FL}	---	---	---
β_{FF}	.21150 (.05060)	.21151 (.05060)	.21151 (.05060)
δ_{FY1}	.05244 (.04724)	.05244 (.04724)	.05244 (.04724)
δ_{FY2}	-.02303 (.03495)	-.02303 (.03495)	-.02303 (.03495)
β_{K2K1}	.00043 (.00049)	.00044 (.00051)	.00044 (.00051)
β_{K2L}	---	---	---
β_{K2F}	---	---	---
δ_{K2Y1}	-.00671 (.00335)	-.00671 (.00335)	-.00603 (.00300)
δ_{K2Y2}	.00464 (.00232)	.00464 (.00232)	.00589 (.00293)
log. det. $\hat{\Sigma}$	-1.54465	-1.54578	4.30815

TABLE 17--Continued

Parameters	Model G-I	Model H-I	Model I-I	Model J-I
α_{K1}	.22081 (.11040)	.22081 (.11040)	.22081 (.11040)	.22002 (.11641)
α_{L}	.13872 (.14981)	.13872 (.14481)	.13872 (.14981)	.13774 (.14972)
α_{F}	.60677 (.40451)	.60677 (.40451)	.60677 (.40451)	.62612 (.42021)
α_{K2}	.01612 (.01135)	.01612 (.01135)	.01612 (.01135)	.01612 (.01135)
β_{K1K1}	.18791 (.03417)	.07142 (.01432)	.07142 (.01432)	.08312 (.01511)
β_{K1L}	.00152 (.00253)	.00018 (.00634)	.00018 (.00634)	.00053 (.00745)
β_{K1F}	.02920 (.02631)	---	---	-.08365 (.07529)
δ_{K1Y1}	.02920 (.02631)	.02815 (.02511)	.02815 (.02511)	---
δ_{K1Y2}	-.03670 (.02531)	-.03613 (.03000)	-.03613 (.03000)	---
β_{LK1}	---	---	---	---
β_{LL}	.04133 (.01562)	.04108 (.01368)	.04108 (.01368)	.04432 (.01766)
β_{LF}	---	-.07222 (.02563)	-.07222 (.02563)	-.04618 (.01603)
δ_{LY1}	-.05143 (.01771)	-.05143 (.01771)	-.05143 (.01771)	---
δ_{LY2}	.05148 (.02575)	.05148 (.02575)	.05148 (.02575)	---
β_{FK1}	---	---	---	---
β_{FL}	---	---	---	---
β_{FF}	.11831 (.03470)	.11831 (.03470)	.11831 (.03470)	.12556 (.02283)
δ_{FY1}	.05244 (.04724)	.05244 (.04724)	.05244 (.04724)	---
δ_{FY2}	-.00189 (.00291)	-.00189 (.00291)	-.00189 (.00291)	---
β_{K2K1}	.00047 (.00053)	.00047 (.00053)	.00047 (.00053)	.00046 (.00052)
β_{K2L}	---	---	---	---
β_{K2F}	---	---	---	---
δ_{K2Y1}	-.01910 (.00907)	-.01910 (.00907)	-.01910 (.00907)	---
δ_{K2Y2}	.01742 (.00913)	.01742 (.00913)	.01742 (.00913)	---
log. det. $\hat{\Sigma}$	2.90028	2.62381	3.05019	2.00829

TABLE 18

PARAMETER ESTIMATES OF THE SHARE EQUATIONS UNDER EXACT MODEL SPECIFICATION (ASYMPTOTIC STANDARD ERRORS IN PARENTHESES)

Vintage III

Parameters	Model A-I	Model B-I	Model C-I
α_{K1}	.31181 (.50619)	.31181 (.50619)	.31181 (.50619)
α_{L}	.11962 (.12117)	.11961 (.12117)	.11961 (.12117)
α_{F}	.53937 (.60148)	.55407 (.61487)	.55407 (.61487)
α_{K2}	.01448 (.36429	.01451 (.36457)	.01451 (.36457)
β_{K1K1}	-.07781 (.03891)	---	-.06138 (.03282)
β_{K1L}	-.03769 (.04932)	---	-.03762 (.04931)
β_{K1F}	-.09185 (.04551)	---	.09900 (.04549)
δ_{K1Y1}	-.10152 (.05343)	---	-.07143 (.03724)
δ_{K1Y2}	.10738 (.03863)	---	.07143 (.02561)
β_{LK1}	-.00985 (.01931)	---	---
β_{LL}	.06957 (.02128)	---	.04354 (.01331)
β_{LF}	-.06951 (.02123)	---	-.08116 (.02573)
δ_{LY1}	-.00451 (.00239)	---	-.00381 (.00202)
δ_{LY2}	.00312 (.00189)	---	.00381 (.00231)
β_{FK1}	.12543 (.39819)	---	---
β_{FL}	-.04115 (.04697)	---	---
β_{FF}	.18105 (.04828)	---	.01784 (.00575)
δ_{FY1}	.17075 (.04955)	---	.10815 (.03138)
δ_{FY2}	-.15006 (.03450)	---	-.10814 (.02487)
β_{K2K1}	-.03516 (.04041)	---	---
β_{K2L}	-.00085 (.00047)	---	---
β_{K2F}	-.00643 (.00487)	---	.06138 (.07039)
δ_{K2Y1}	-.02037 (.00509)	---	-.14031 (.03431)
δ_{K2Y2}	.01648 (.00364)	---	.14031 (.03093)
log. det. $\hat{\Sigma}$	-1.86003	3.00589	2.04614

TABLE 18 --Continued

Param-eters	Model D-I	Model E-I	Model F-I
α_{K1}	.21004 (.16351)	.21004 (.16351)	.21005 (.61387)
α_{L}	.17103 (.13401)	.17103 (.13401)	.21005 (.48951)
α_{F}	.57620 (.22247)	.57620 (.22247)	.53937 (.60148)
α_{K2}	.01809 (.01146)	.01809 (.01146)	.01449 (.36429)
β_{K1K1}	.12461 (.06572)	.12461 (.06572)	-.07700 (.03528)
β_{K1L}	.06310 (.06939)	.06310 (.06439)	-.03769 (.04932)
β_{K1F}	-.00522 (.02147)	-.07112 (.06333)	-.07001 (.03502)
δ_{K1Y1}	-.03102 (.02795)	-.03124 (.02721)	-.00183 (.00092)
δ_{K1Y2}	.02117 (.02406)	.02148 (.02455)	.08104 (.02914)
β_{LK1}	---	---	---
β_{LL}	.00153 (.02887)	.00154 (.02887)	.06954 (.03148)
β_{LF}	-.04938 (.02147)	-.05791 (.02518)	-.06950 (.02126)
δ_{LY1}	-.05001 (.00997)	-.02544 (.00509)	-.00442 (.00231)
δ_{LY2}	.03102 (.01449)	.01749 (.00833)	.00312 (.00189)
β_{FK1}	---	---	---
β_{FL}	---	---	---
β_{FF}	-.05960 (.03281)	-.65960 (.03281)	.13158 (.03618)
δ_{FY1}	.10006 (.03156)	.10006 (.03156)	.17072 (.04950)
δ_{FY2}	-.06089 (.06037)	-.06089 (.06038)	-.15002 (.03447)
β_{K2K1}	---	---	---
β_{K2L}	---	---	---
β_{K2F}	.03002 (.02981)	.03002 (.02981)	-.03510 (.04038)
δ_{K2Y1}	-.00529 (.00541)	-.00024 (.00025)	-.00183 (.00049)
δ_{K2Y2}	.00328 (.00351)	.00064 (.00065)	.08104 (.02241)
log. det. $\hat{\Sigma}$	-3.14862	-3.20016	4.18259

TABLE 18--Continued

Param-eters	Model G-I	Model H-I	Model I-I	Model J-I
α_{K1}	.31181 (.50619)	.31181 (.50619)	.31181 (.50619)	.31180 (.50619)
α_{L}	.11962 (.12117)	.11962 (.12117)	.11962 (.12117)	.11962 (.12117)
α_{F}	.53937 (.60148)	.53937 (.60148)	.53937 (.60148)	.53937 (.60148)
α_{K2}	.01447 (.36429)	.01447 (.36429)	.01447 (.36429)	.01448 ( )
β_{K1K1}	-.07781 (.03891)	-.06132 (.03280)	-.06132 (.03280)	-.07781 (.03891)
β_{K1L}	-.03769 (.04932)	-.03753 (.04920)	-.03753 (.04920)	-.03301 (.04601)
β_{K1F}	-.09185 (.04551)	---	---	-.05168 (.02899)
δ_{K1Y1}	-.10152 (.05343)	.09900 (.04549)	.09900 (.04549)	---
δ_{K1Y2}	.10738 (.03863)	-.07141 (.03723)	-.07141 (.03723)	---
β_{LK1}	---	---	---	---
β_{LL}	.04351 (.01330)	.06957 (.02128)	.06957 (.02128)	.04081 (.02005)
β_{LF}	---	-.06951 (.02123)	-.06951 (.02123)	-.05382 (.01892)
δ_{LY1}	-.00406 (.00202)	-.00451 (.00239)	-.00451 (.00239)	---
δ_{LY2}	.00315 (.00190)	.00312 (.00189)	.00312 (.00189)	---
β_{FK1}	---	---	---	---
β_{FL}	---	---	---	---
β_{FF}	.18105 (.04828)	.18105 (.04828)	.18105 (.04828)	.01874 (.00575)
δ_{FY1}	.17075 (.04955)	.17075 (.04955)	.17075 (.04955)	---
δ_{FY2}	-.15006 (.03450)	-.15006 (.03450)	-.15006 (.03450)	---
β_{K2K1}	---	---	---	---
β_{K2L}	---	---	---	---
β_{K2F}	-.03512 (.04039)	-.03512 (.04039)	-.03512 (.04039)	.00398 (.00529)
δ_{K2Y1}	-.00085 (.00047)	-.00085 (.00047)	-.00085 (.00047)	---
δ_{K2Y2}	-.00642 (.00487)	-.00642 (.00487)	.00642 (.00487)	---
log. det. $\hat{\Sigma}$	3.11053	-1.99312	-1.99386	3.56679

TABLE 19

PARAMETER ESTIMATES OF THE COST UNDER APPROXIMATE MODEL SPECIFICATION (ASYMPTOTIC STANDARD ERRORS IN PARENTHESES)

Parameters	Model		
	A-II	B-II	C-II
α_K	.28016 (.08175)	.28016 (.08175)	.28016 (.08175)
α_L	.14301 (.12007)	.14301 (.12007)	.14301 (.12007)
α_F	.57192 (.22241)	.57683 (.22432)	.57683 (.22432)
β_{KK}	.17002 (.05914)	---	.11827 (.06957)
β_{KL}	-.01072 (.02143)	---	-.01079 (.02149)
β_{KF}	-.10742 (.03181)	---	-.10748 (.03186)
δ_{KY1}	-.05001 (.03061)	---	---
δ_{KY2}	.05811 (.02318)	---	---
β_{LK}	-.02012 (.02148)	---	---
β_{LL}	.04181 (.01347)	---	.05016 (.01254)
β_{LF}	-.03810 (.03800)	---	-.03937 (.03922)
δ_{LY1}	-.57740 (.10310)	---	---
δ_{LY2}	.00142 (.00060)	---	---
β_{FK}	-.15172 (.05889)	---	---
β_{FL}	-.02998 (.03114)	---	---
β_{FF}	.14051 (.02001)	---	.14685 (.02098)
δ_{FY1}	.12501 (.02117)	---	---
δ_{FY2}	-.10381 (.02703)	---	---
η_K	.04413 (.02918)	---	.04410 (.02912)
η_L	-.00185 (.00103)	---	-.00185 (.00103)
η_F	.04318 (.02703)	---	.04308 (.20497)
ψ_{Y1}	-.21810 (.20516)	---	---
ψ_{Y2}	-.39158 (.32015)	---	---
ω	.05773 (.01889)	---	---
ϕ	-.50369 (.25668)	---	-.46318 (.23569)
θ_1	.02318 (.01059)	---	.02312 (.01042)
θ_2	.02119 (.01009)	---	.02119 (.01009)
λ	5.03127 (.00167)	13.05186 (.00433)	5.10318 (.01638)
γ_{Y1}	.97185 (.03187)	.96143 (.03126)	1.00000
γ_{Y2}	.74159 (.34182)	.71037 (.32639)	.75003 (.34461)
ξ	-.01168 (.13121)	-.01168 (.13121)	-.01168 (.13123)
log. det. $\hat{\Sigma}$	1.01005	2.98116	1.40012

TABLE 19-Continued

Param- eters	Model D-II	E-II	F-II
α_K	.28016 (.08175)	.28016 (.08175)	.28016 (.08175)
α_L	.14301 (.12007)	.14301 (.12007)	.14301 (.12007)
α_F	.57683 (.22432)	.57683 (.22432)	.57683 (.22432)
β_{KK}	.11827 (.06957)	.11827 (.06957)	.11827 (.06957)
β_{KL}	-.01079 (.02149)	-.01079 (.02149)	-.01079 (.02149)
β_{KF}	-.10748 (.03186)	-.10748 (.03186)	-.10748 (.03186)
δ_{KY1}	-.05008 (.03062)	-.05008 (.03062)	-.05008 (.03062)
δ_{KY2}	.05008 (.01792)	.05008 (.01792)	.05008 (.01792)
β_{LK}	---	---	---
β_{LL}	.05106 (.01254)	.05016 (.01254)	.05016 (.01254)
β_{LF}	-.03937 (.03922)	-.03937 (.03922)	-.03937 (.03922)
δ_{LY1}	-.38116 (.12489)	-.38116 (.12489)	-.38116 (.12489)
δ_{LY2}	.38116 (.19005)	.38116 (.19005)	.38116 (.19005)
β_{FK}	---	---	---
β_{FL}	---	---	---
β_{FF}	.14685 (.02098)	.14685 (.02098)	.14685 (.02098)
δ_{FY1}	.11663 (.01731)	.11663 (.01731)	.11663 (.01731)
δ_{FY2}	-.11663 (.01993)	-.11663 (.01993)	-.11663 (.01993)
η_K	.04410 (.02912)	.04410 (.02912)	---
η_L	-.00185 (.00103)	-.00185 (.00103)	---
η_F	.04308 (.20497)	.04308 (.20497)	---
ψ_{Y1}	-.21810 (.20516)	-.21302 (.20248)	-.21810 (.20516)
ψ_{Y2}	-.39158 (.32015)	-.39106 (.32000)	-.39158 (.32015)
ω	.05773 (.01889)	---	.05773 (.01889)
ϕ	-.45132 (.22918)	-.45132 (.22918)	-.36128 (.21314)
θ_1	.02312 (.01042)	.02312 (.01042)	---
θ_2	.02119 (.01009)	.02119 (.01009)	---
λ	5.10318 (.01638)	5.10318 (.01638)	5.11641 (.01749)
γ_{Y1}	.97183 (.03186)	.97183 (.03186)	.97183 (.03186)
γ_{Y2}	.74148 (.34181)	.74148 (.34181)	.74148 (.34181)
ξ	.01168 (.13123)	.01168 (.13123)	.01168 (.13123)
log. det. $\hat{\Sigma}$	1.17932	1.20153	1.39310

TABLE 19--Continued

Parameters	Model G-II	Model H-II	Model I-II
α_K	.28103 (.08200)	.28016 (.08175)	.28016 (.08175)
α_L	.14291 (.12249)	.14301 (.12007)	.14301 (.12007)
α_F	.57103 (.21660)	.57192 (.22241)	.57192 (.22241)
β_{KK}	.11823 (.06950)	.18103 (.06389)	.17301 (.05739)
β_{KL}	-.01073 (.02141)	-.01171 (.02573)	-.01072 (.02318)
β_{KF}	-.10531 (.02872)	-.11838 (.02960)	---
δ_{KY1}	-.05000 (.03000)	-.05003 (.03065)	-.05011 (.03083)
δ_{KY2}	.05213 (.02607)	.05980 (.01897)	.05618 (.01589)
β_{LK}	---	---	---
β_{LL}	.05016 (.01254)	.05023 (.01199)	.05023 (.01199)
β_{LF}	-.05355 (.05341)	---	-.05071 (.05106)
δ_{LY1}	-.02543 (.00438)	-.57740 (.10310)	-.57741 (.10310)
δ_{LY2}	.02651 (.01326)	.00142 (.00068)	.02651 (.01326)
β_{FK}	---	---	---
β_{FL}	---	---	---
β_{FF}	.14685 (.02098)	.14673 (.02054)	.11718 (.01562)
δ_{FY1}	.11663 (.01731)	.12541 (.02069)	.11610 (.01900)
δ_{FY2}	-.11663 (.01993)	-.10227 (.01932)	-.10227 (.01932)
η_K	.04413 (.02207)	.04410 (.02912)	.04410 (.02912)
η_L	.02244 (.01244)	-.00132 (.00053)	-.00138 (.00055)
η_F	.04308 (.20497)	.04308 (.20497)	.01065 (.05208)
ψ_{Y1}	-.21810 (.20516)	-.20217 (.20019)	-.21809 (.20522)
ψ_{Y2}	-.39158 (.32015)	-.39127 (.32006)	-.39137 (.32021)
ω	.05773 (.01889)	.05683 (.01622)	.05694 (.01630)
ϕ	-.45132 (.22918)	-.45132 (.22918)	-.45132 (.22918)
θ_1	.02312 (:01042)	.02312 (.01042)	.02312 (.01042)
θ_2	.02119 (.01009)	.02119 (.01009)	.02119 (.01009)
λ	5.10400 (.01543)	5.11641 (.01749)	5.14381 (.01993)
γ_{Y1}	.98138 (.03238)	.97003 (.03009)	.97113 (.03021)
γ_{Y2}	.74787 (.34861)	.74140 (.34171)	.74516 (.34231)
ξ	-.01168 (.13123)	-.01168 (.13123)	.01168 (.13123)
log. det. $\hat{\Sigma}$	1.19896	1.30510	2.00510

TABLE 19--Continued

Param-eters	Model		
	J-II	K-II	L-II
α_K	.28016 (.08175)	.28016 (.08175)	.28016 (.08175)
α_L	.14301 (.12007)	.14301 (.12007)	.14301 (.12007)
α_F	.57192 (.22241(	.57192 _.22241)	.57192 (.22241)
β_{KK}	.11827 (.06957)	.17002 (.05914)	.18103 (.06384)
β_{KL}	-.01079 (.02149)	-.01072 (.02143)	-.01171 (.02573)
β_{KF}	-.10748 (.03186)	-.10742 (.03180)	-.11838 (.02960)
δ_{KY1}	---	-.05001 (.03061)	-.05003 (.03065)
δ_{KY2}	---	-.00216 (.01038)	.05980 (.01897)
β_{LK}	-.01885 (.01993)	-.02009 (.02133)	-.03000 (.02309)
β_{LL}	.05016 (.01254)	.04173 (.01321)	.04182 (.01349)
β_{LF}	-.03932 (.03917)	-.03661 (.03651)	-.03812 (.03802)
δ_{LY1}	---	.53104 (.21005)	-.57740 (.10310)
δ_{LY2}	---	-.00038 (.00041)	.00142 (.00068)
β_{FK}	-.14106 (.04798)	-.15172 (.05889)	-.16220 (.05765)
β_{FL}	-.03007 (.03126)	-.01098 (.02441)	-.03558 (.03321)
β_{FF}	.14218 (.02009)	.14051 (.02001)	.16500 (.02891)
δ_{FY1}	---	.12501 (.02117)	.12541 (.02069)
δ_{FY2}	---	-.10381 (.02703)	-.10227 (.01932)
η_K	.04410 (.02912)	.04413 (.02918)	---
η_L	-.00185 (.00103)	-.00181 (.00097)	---
η_F	.04311 (.20501)	.04318 (.02703)	---
ψ_{Y1}	-.20316 (.20045)	-.18168 (.17937)	-.20316 (.20045)
ψ_{Y2}	-.38979 (.31771)	-.30912 (.26173)	-.38983 (.31776)
ω	.05682 (.01630)	---	.05691 (.01638)
ϕ	.45132 (.23381)	-.50369 (.25668)	---
θ_1	.02312 (.01042)	.01131 (.00516)	---
θ_2	.02119 (.01009)	.03885 (.01938)	---
λ	5.06118 (.00239)	5.06121 (.00246)	5.10318 (.00169)
γ_{Y1}	.97106 (.03055)	.97103 (.03051)	.96687 (.02990)
γ_{Y2}	.74138 (.34109)	.74130 (.34097)	.73877 (.33943)
ξ	-.01168 (.13123)	-.01168 (.13123)	---
log. det. $\hat{\Sigma}$	1.26392	1.11003	1.28731

VITA

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